# Bulletin

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## PAPERS IN PRESS FOR FORTHCOMING ISSUES

CRYSTALLINE ROCKS OF SOUTHERN CALIFORNIA. By William J. Miller

TERTIARY AND QUATERNARY GEOLOGY OF THE LOWER RIO PUERCO AREA, NEW MEXICO. By Herbert E. Wright, Jr.*

Contains three colored maps: Geologic map of Lower Rio Puerco area, 16″ by 13″, scale about 1″ = 3 miles; Geomorphic map of Lower Rio Puerco area, 16″ by 15″, scale about 1″ = 3 miles; and Geologic map and structure sections of Lucero fault zone, 16″ by 7″, scale about 1″—2000′ ($.50 for set of three)

GEOLOGY OF THE NORTHWESTERN WIND RIVER MOUNTAINS, WYOMING. By C. L. Baker*

Contains colored geologic map of part of Fremont Peak quadrangle, U. S. G. S. topographic sheet as base. Scale, 1″ = 2 miles ($.25 each)

GRAIN-SHAPE FABRICS OF CLASTIC QUARTZ. By Richards A. Rowland

QUARTZ CRYSTAL IN BRAZIL. By W. D. Johnston, Jr., and Robert D. Butler

CAMBRIAN AND EARLY ORDOVICIAN STRATIGRAPHY OF THE LOWER ST. LAWRENCE VALLEY. By Franco Rasetti

*As an innovation, and for a trial period, we shall have available for separate purchase 100 unfolded copies (in tubes, at prices indicated) of colored maps appearing in the Bulletin. Orders will be filled as long as the supply lasts.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 295-308, 15 FIGS. APRIL 1946

# NAVIGATION IN CRYSTALLOGRAPHY

BY HORACE WINCHELL

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## ABSTRACT

The similarity between obtaining a "fix" of location and course by using a zenith camera to photograph the position of the stars, and determining the orientation of a crystal such as diamond or corundum by using the back-reflection Laue method has led to the term, crystal navigation. The two techniques are strikingly similar except that the crystal navigator does not need a chronometer. Longitude, latitude, and course have analogues in crystallography; and an error in "setting the course" or in determining a position may make a jewel bearing fail or a diamond cutter wear badly or break. The several crystal projections—sterographic, gnomonic, back-reflection Laue, and forward-reflection Laue—are discussed. The back-reflection projection and the gnomonic projection together constitute an efficient and reasonably simple system for crystal navigation. The technique of crystal navigation in corundum and in diamond is illustrated by charts. The practical usefulness of the system is shown by reference to diamond-tool design.


## INTRODUCTION

"Navigation" is often taken to imply the use of observations of stars and other bodies to determine the position of the observer's zenith with reference to the celestial sphere, and hence, knowing the time of the observation, with reference to the conventional system of lines of longitude and latitude on the earth. As used in this article, "navigation" in a crystal implies the analogous use of observations of crystallographic "stars"—the points representing crystal planes in a back-reflection Laue diagram or in the corresponding gnomonic projection—to determine the two-circle goniometer co-ordinates "longitude" and "colatitude" of a plane in the crystal. In describing the direction or azimuth of a ship's course, the navigator uses a scale of degrees reading 0° for north, 90° for east, 180° for south, and so on. Similarly it may be necessary to specify a certain direction or azimuth on the surface of the crystal.

Some mineralogical examples will illustrate the necessity of knowing crystallographic orientation. Consider for a moment the mineral kyanite. Most elementary mineralogy students know that the hardness of this mineral varies with the direction in which a scratch test is made on the surface of the specimen. Few would be able to describe accurately, however, either the orientation of the surface or the direction of scratching. A simple experiment with Iceland spar and fine sandpaper will demonstrate further the directional properties of a plane crystal surface. There is a noticeable difference in resistance of the crystal to abrasion by the sandpaper in the various directions in a cleavage surface of the mineral. A conspicuous difference exists among the several directions in a surface parallel to the base c(0001), for the tendency of the crystal to yield by glide twinning on $(01\bar{1}2)$ makes it almost impossible to grind the pinacoid toward the positive rhombohedral zone.

In the above examples, natural crystal surfaces have been used to specify approximately both surface and direction. When shaped crystals are employed for machining operations, artificial surfaces are involved which may not be so convenient to specify exactly by Miller indices. Yet their orientation may greatly affect the life of the tool. That such a factor may be of economic importance has been adequately proved, for a certain type of diamond tool may show more wear from producing 200 units if the crystal is improperly oriented, than from producing 20,000 units if it is favorably oriented. All three crystal orientation co-ordinates—longitude, colatitude,

azimuth—must be controlled properly in this case. If errors are made in cutting or setting such a tool, the crystallographer may have to navigate to the desired orientation by indicating to the machinist or to the diamond cutter what corrections are needed.

The purpose of this paper is to call attention to certain relations that will inevitably be found by a crystallographer in the navigation of the comparatively uncharted regions of the crystal world. We shall first briefly review the representation of a crystal by projections, and set up definitions of crystal "longitude," crystal "latitude," and crystal "azimuth." We can then consider briefly some applications.

## ACKNOWLEDGMENT

It is a pleasure to acknowledge the assistance of Mr. G. E. Shubrooks, Chief Chemist and Metallurgist, and of Mr. R. W. Henry, Supervisor of the Metals Processing Department, of the Hamilton Watch Co., in making extensive measurements during production runs. Thanks are due many other departmental foremen for their patient co-operation in what probably seemed at the time to be slowly evolving experiments of uncertain value. Miss C. I. Neetzow and Miss M. E. Gaus contributed much in recording results, analyzing x-ray patterns, and proving the practicability of the system in constant usage. Mr. B. L. Hummel supervised the preparation of the illustrations.

## PROJECTIONS USED IN CRYSTAL NAVIGATION

### GNOMONO-STEREOGRAPHIC PROJECTION

Two projections, the stereographic and the gnomonic, are familiar to all crystallographers and to cartographers and geologists. Their relationships to one another have been described by many authors (*e.g.*, Dana-Ford, 1932, p. 48; A. N. Winchell, 1933, p. 1; Deetz and Adams, 1934, p. 44.) Some of these relations are shown in Figure 1. The line NSG represents the plane of the gnomonic projection, into which the stereographic projection has also been carried from OS′. OP represents a plane of atoms in the crystal. The normal to the plane OP through O cuts the reference sphere at M and the gnomonic plane at G. The point G is the gnomonic projection of OP and of all parallel planes. A line from M to the lower pole of the sphere cuts the equatorial plane at S′, which is the stereographic projection of OP. For convenience, S′ is carried up to S in the gnomono-stereographic plane NSG. The geometry is such that the angle NOS is half as great as the angle NOG; NOG is equal to the angle of inclination, I, of the plane OP. The distances NS and NG are given by the following equations, in which R is the distance NO:

$$NS = R \tan \tfrac{1}{2}I \quad \textit{Stereographic equation} \quad (1)$$

$$NG = R \tan I \quad \textit{Gnomonic equation} \quad (2)$$

### BACK-REFLECTION AND FORWARD-REFLECTION LAUE PROJECTIONS

Defining the term "projection" to mean a representation of the planes of atoms of the crystal-lattice by means of points such that there is a point in the projection for every set of parallel atomic planes in the crystal, and so that there is in the crystal a

set of such planes for every point indicated in the projection, results in a one-to-one correspondence between the points of the projection and the sets of parallel atomic planes in the crystal. As just shown for the gnomonic and stereographic projections, so also for the two Laue projections obtained by passing a narrow beam of x-rays, NO in the figure, through the crystal and recording on sensitive films N′B and N″L the reflections of that beam produced by the various families of planes in the crystal. The position of the point representing a plane is determined by the inclination of the plane with respect to the primary x-ray beam, and by the position of the film. Thus the plane OP (Fig. 1) would reflect a portion of the energy of the primary x-ray beam NO to the point B. This takes place in accordance with the usual law of reflection which states that the angles of incidence, NOG, and of reflection, GOB, are equal. Such a reflected beam will be produced if the primary beam contains radiation which satisfies Bragg's law relating wave length and atomic spacing to angle of incidence. The equation for the Laue back-reflection projection is therefore:

$$N'B = D \tan 2I \quad \text{Back-reflection Laue equation} \quad (3)$$

It will be evident that if the plane OP had been inclined at an angle greater than 45°, then the reflected beam would not pass to the back-reflection plane N′B but to the forward-reflection plane N″L. This is the conventional position of the film when making a Laue diffraction pattern from a crystal. Nevertheless, N′B, the back-reflection plane, logically belongs to the Laue projection just as much as N″L. One or the other of these two planes will receive any rays that can be reflected in accordance with Bragg's law. Equation (3), if properly interpreted when minus signs appear, will also hold for the forward-reflection half of the Laue projection. However, it is usually written thus:

$$N''L = D \tan (180° - 2I) \quad \text{Forward-reflection Laue equation} \quad (4)$$

### INTERRELATIONS OF THE PROJECTIONS

The three projections, stereographic, gnomonic, and Laue, constitute a convenient system for crystal navigation. The Laue projection is necessarily the one recorded upon x-ray films; the back-reflection half is more useful in this work because of its similarity in appearance to the gnomoic projection. The forward-reflection half can also be used, but its interpretation is more difficult and can add nothing to the result obtained from the back-reflection half. The gnomonic projection has been found more convenient for crystal navigation than the stereographic. The utility of the gnomonic and the back-reflection Laue projections for crystal navigation is improved if R (the scale of the gnomonic projection) is made about $2\frac{1}{2}$ times as large as D (the crystal-film distance; *see* Figure 1). Under these conditions, the two projections appear very similar. Setting R = 5 cm. and D = 2 cm. makes possible the use of a readily available projection protractor (Fisher, 1941).

## DEFINITIONS AND PROCEDURE

### CRYSTAL CO-ORDINATES

In a study of the effects of orientation on corundum fabrication (H. Winchell, 1944), it was sufficient to express longitude and colatitude of a crystal plane, the

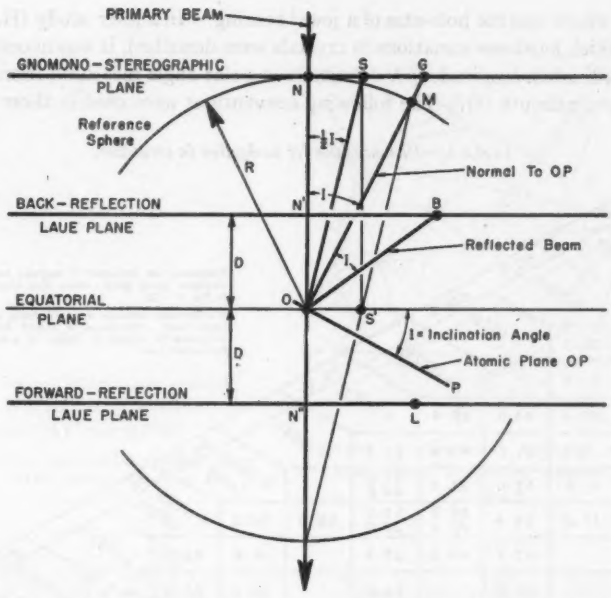


FIGURE 1.—*Relations among the stereographic, the gnomonic, the back-reflection Laue, and the forward-reflection Laue projections*

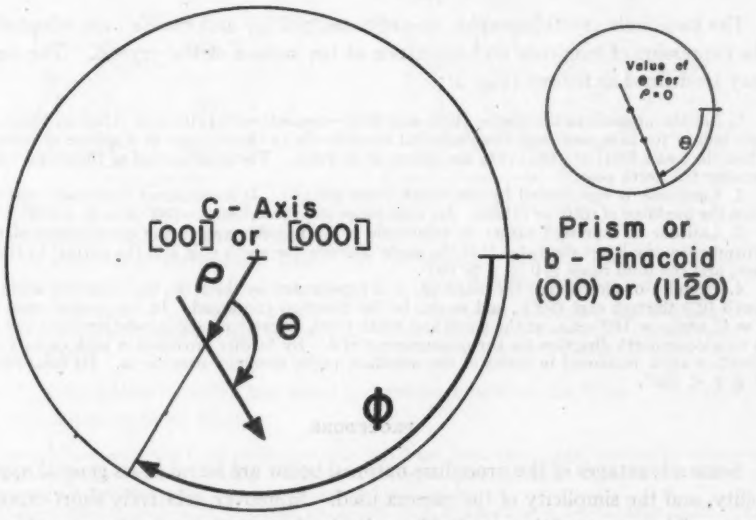


FIGURE 2.—*Stereographic projection illustrating the definitions of φ and ρ, the angular co-ordinates of a crystal surface, and of θ, a direction in that surface*

For a plane normal to the c-axis, $\rho = 0$, $\varphi$ is indeterminate, and $\theta$ is specially defined, as shown on the small diagram, by the direction angle measured on the longitude scale usually used for $\varphi$.

normal of which was the hole-axis of a jewel bearing. In a later study (H. Winchell, 1945) in which hardness variations in crystals were described, it was necessary to use three co-ordinates: longitude ($\varphi$), colatitude or polar angle measured from the north pole ($\rho$), and azimuth ($\theta$). The following conventions were used in those studies.

TABLE 1.—*Distance table for navigation in corundum*

| X → / c (0001) | m (10$\bar{1}$0) 60.0 | a (11$\bar{2}$0) 60.0 | q (20$\bar{2}$5) 86.0 | r (10$\bar{1}$1) | f (40$\bar{4}$1) 64.8 | R (01$\bar{1}$2) (10$\bar{1}$2) 78.7 | s (02$\bar{2}$1) (20$\bar{2}$1) | p (11$\bar{2}$3) 52.0 | n (22$\bar{4}$3) | i (21$\bar{3}$1) (3$\bar{1}$21) *(12$\bar{3}$1) |
|---|---|---|---|---|---|---|---|---|---|---|
| 90 0 | | | | | | | | | | |
| 90 0 | 30.0 | | | | | | | | | |
| 32 2 | 57 8 | | | | | | | | | |
| 57 6 | 32 4 | 43 0 | 25.4 | | | | | | | |
| 81 0 | 9 0 | 31 2 | 48 8 | 23.4 | | | | | | |
| 38 2 | *51.8* | 57 6 | 33.9 | 47.0<br>*84.2* | | R (01$\bar{1}$2) (10$\bar{1}$2) | | | | |
| 72 4 | *17.6* | 34 4 | 59.3<br>*75.4* | 55.6<br>*50.0* | 58.8 | 34.2 | s (02$\bar{2}$1) (20$\bar{2}$1) | | | |
| 42 3 | | 47.7 | 20.5 | 27.3 | | 19.6 | 38.8 | p (11$\bar{2}$3) | | |
| 61 2 | | 28.8 | | 26.0 | | 32.0 | 30.5 | 18.9 | n (22$\bar{4}$3) | |
| | | 17.3 | | 25.7 | 19.2 | 50.4 | 39.5<br>*36.4 | *53.0* | 18 4 | i (21$\bar{3}$1) (3$\bar{1}$21) *(12$\bar{3}$1) |

Distances are indicated in degrees and decimals along great-circle arcs shown in Fig. 5 - 10.

X = Distance between adjacent faces of same form. Distances in *italics* are measured to planes in *italics* in same horizontal row

The two-circle crystallographic co-ordinates, phi ($\varphi$) and rho ($\rho$), are adopted for the expression of longitude and colatitude of the surface of the crystal. The angles may be defined as follows (Fig. 2):

1. Let the normals to the planes (100) and (010)—respectively (2$\bar{1}\bar{1}$0) and ($\bar{1}$2$\bar{1}$0) in Miller-Bravais indices for hexagonal and rhombohedral crystals—lie in the equator of a sphere of reference. Then the *c*-axis [001] or [0001] cuts the sphere at its poles. The positive end of the *c*-axis will determine the north pole.
2. Longitude is represented by the Greek letter phi ($\phi$). It is measured clockwise (westward) from the meridian of (010) or (11$\bar{2}$0). Its total range may be written: $-180° < \phi \leqq +180°$.
3. Latitude is expressed rather as colatitude or north-polar angle—the complement of north latitude—by the letter rho ($\rho$). It is the angle between the north pole and the normal to the surface, and the total range is $0 \leqq \rho \leqq 180°$.
4. Azimuth or direction in the plane ($\phi$, $\rho$) is represented by theta ($\theta$), the clockwise angle from north (0°) through east (90°), and so on, to the direction concerned. In the special cases when $\rho = 0°$ and $\rho = 180°$—*i.e.*, at the north and south poles, respectively—$\phi$ is indeterminate and there is no unique north direction for the measurement of $\theta$. By further provision in such cases, $\theta$ is the direction angle measured in terms of the meridian angles normally used for $\phi$. Its total range is $0 \leqq \theta < 360°$.

## PROCEDURE

Some advantages of the procedure outlined below are found in its general applicability, and the simplicity of the camera used. Moreover, relatively short exposures are possible because of the use of white radiation from the tube, and because of a short crystal-film distance. A disadvantage for some purposes is the order of accuracy attainable with short exposures. The co-ordinate angles $\varphi$, $\rho$, and $\theta$, are accurate to

FIGURE 3.—*Back-reflection Laue pattern (retouched) of a portion of the corundum crystal "sky" near r(10$\bar{1}$1)*

Made from a hardness-tested specimen which was scratched in the direction shown by the arrow.

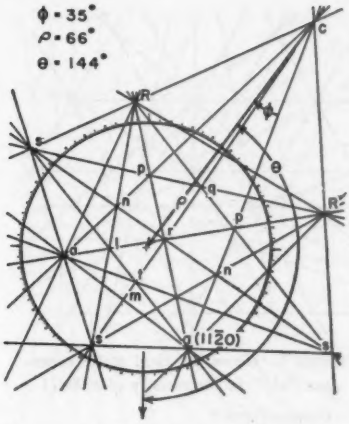


FIGURE 4.—*Gnomonic projection made from Figure 3, showing location of φ, ρ, and θ*

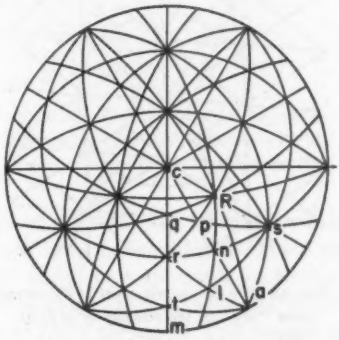


FIGURE 5.—*Stereographic master-chart of the corundum "sky", indicating principal zones prominent in backreflection Laue patterns*

The forms indicated are $c(0001)$, $m(10\bar{1}0)$, $a(11\bar{2}0)$, $q(20\bar{2}5)$, $r(10\bar{1}1)$, $R(01\bar{1}2)$, $s(02\bar{2}1)$, $p(11\bar{2}3)$, $n(22\bar{4}3)$, $l(21\bar{3}1)$.

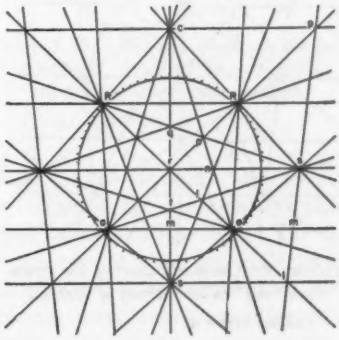

FIGURE 6.—*Gnomonic chart of the corundum "sky" in the vicinity of r(10$\bar{1}$1)*

This aspect identifies most clearly the pseudo-cubic symmetry of the mineral. *Compare* Figure 13 for a cubic lattice in corresponding orientation.

about 2° with ordinary care in the setup and measurement of the films. The procedure followed is outlined below:

1. Record back-reflection Laue projection with film 2 cm. from the crystal, parallel to unknown crystal plane, and normal to primary x-ray beam. A significant direction—if any—in the crystal plane must be noted with respect to top or edge of film (Fig. 3).
2. Convert film projection to gnomonic projection (Fig. 4) based on a 5-centimeter unit. The projection protractor described by Fisher (1941) is helpful if the 2-centimeter scale is renumbered to make a back-reflection scale.
3. With the help of a master chart of the crystal (Fig. 5), and/or appropriate distance tables (Table 1), identify as many projected points or zones as necessary, and locate position of equatorial

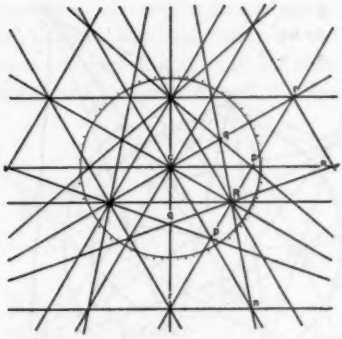

FIGURE 7.—*Gnomonic chart of the corundum "sky" in the vicinity of c(0001)*

*Compare* Figure 8.

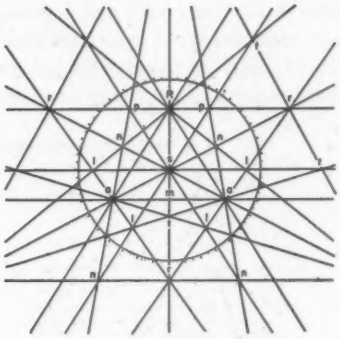

FIGURE 8.—*Gnomonic chart of the corundum "sky" in the vicinity of s(02$\bar{2}$1)*

Note slight differences from Figure 7.

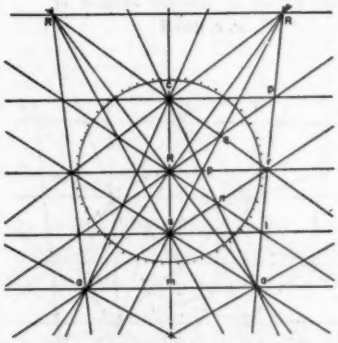

FIGURE 9.—*Gnomonic chart of the corundum "sky" in the vicinity of R(01$\bar{1}$2)*

*Compare* Figure 10.

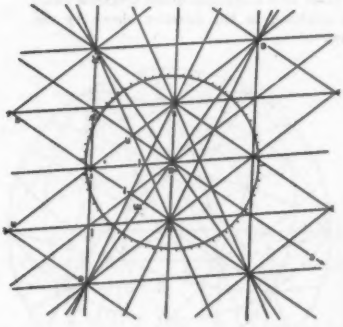

FIGURE 10.—*Gnomonic chart of the corundum "sky" in the vicinity of a(11$\bar{2}$0)*

The pattern for a'($\bar{1}$2$\bar{1}$0) is a mirror image of this.

zone or of *c*-axis. Distances may be noted on the master chart as on a road map. Angles between zone lines at important intersections may also be indicated on the chart and used for identification. A gnomonic net (Fig. 11) is very useful for this identification work, and graphical methods may be used to supplement the measurements made with the net.

4. Measure colatitude or polar angle $\rho$ by distance from *c*-axis to center of projection, using suitable tangent scale or Fisher's projection protractor. The latitude ($90° - \rho$) may be easier to measure if the equator passes close to center of the projection.

5. Measure longitude angle $\phi$ clockwise about *c*-axis as center (Fig. 4), from prime meridian to line between center and *c*-axis. This measurement is made by the procedure given by Fisher (1941, p. 424) under the heading of "Angle problem." Often $\phi$ can be more accurately obtained by measuring the angle to a recognizable meridian other than the prime meridian.

6. Measure azimuth $\theta$ clockwise about center of projection from line through center and *c*-axis, to line through center in significant direction noted in step 1 above.

It will be seen that the above procedure is essentially the same as that which would be involved in fixing the longitude, latitude, and course of a ship at sea from a photo-

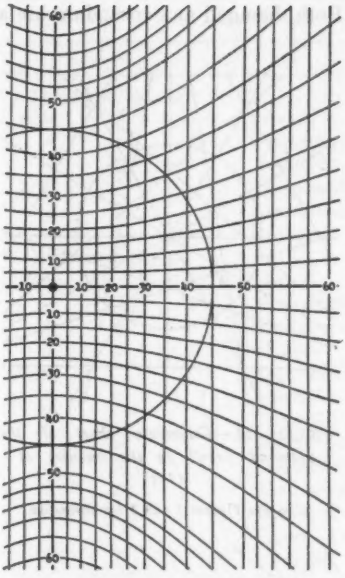

FIGURE 11.—*Gnomonic net for measuring "distances" (angles along great circles) between points in the gnomonic projection*

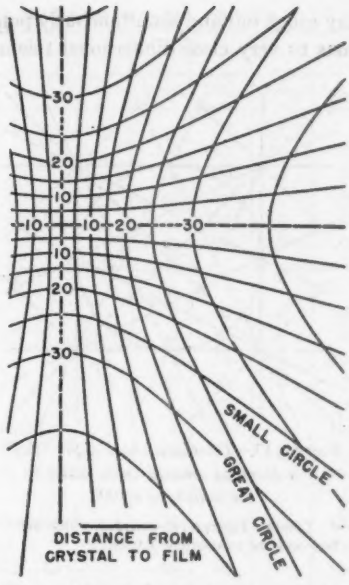


FIGURE 12.—*Back-reflection Laue net for measuring "distances" between points in back-reflection Laue patterns*

*Compare* Figure 11.

graph of the night sky made by pointing a camera toward the zenith, the top of the picture being in the direction of the ship's bow. Indeed, the zenith-camera photograph would be a gnomonic projection and would be measured as such. The main differences are (1) that the crystal is fixed with respect to the projection while the ship rotates (with the earth) with respect to the stars, making a time observation necessary; and (2) that symmetry of the crystal produces symmetries and repetitions of the crystal "sky" or projection, so that a given pattern may have several interpretations corresponding to symmetrically equivalent positions of the crystal. Difference (2) actually results in a simplification, for limits depending upon the symmetry of the crystal class, shown in Table 2, may be set for the orientation angles $\varphi$ and $\rho$. In general, $\theta$ cannot be limited to less than its full range from 0° to 360°, except if the plane ($\varphi$, $\rho$) falls normal to an axis of symmetry or to a plane of symmetry.

## APPLICATIONS

### GENERAL STATEMENT

Single crystals of diamond and corundum are often used industrially as shaped tools for machining operations. For example, a shaped diamond or sapphire cutter

may rough out and simultaneously polish gold, brass, and similar metals, finishing the parts to very close dimensional tolerances. Both diamond and corundum are also

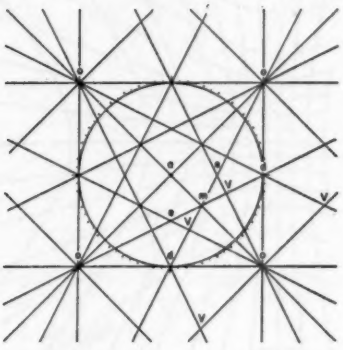

FIGURE 13.—*Gnomonic chart of the "sky" of a diamond-centered cubic lattice in the vicinity of a(100)*

*Compare* Figure 6 for corundum which has a face-centered pseudocubic lattice.

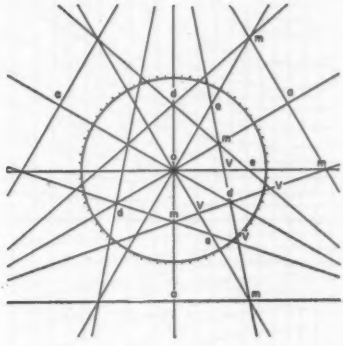

FIGURE 14.—*Gnomonic chart of the diamond "sky" in the vicinity of o(111)*

*Compare* Figures 7 and 8 for corundum.

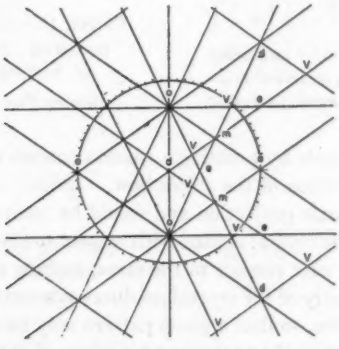

FIGURE 15.—*Gnomonic chart of the diamond "sky" in the vicinity of d(110)*

*Compare* Figures 9 and 10 for corundum.

made into watch and instrument bearings and wire dies. At present, diamond is pre-eminent for tools and dies, and corundum for jewel bearings.

Orientation plays an important part in the fabrication and wearing qualities of corundum jewel bearings. H. Winchell (1944) showed that certain orientations lead to greater spoilage in fabrication than others. Other studies (Stott, 1931; Sandmeier, 1933) have shown a direct relation between orientation and service life of jewel bearings. Corundum also has a noticeable "grain" which must be oriented properly to avoid excessive chipping and untimely wear when used for lathe tools.

Considering only diamond and corundum, there is ample reason for development of

TABLE 2.—*Limits of variation of φ and ρ resulting from crystal symmetry*

| Symmetry Class | | | | φ | | ρ | |
|---|---|---|---|---|---|---|---|
| Symbol | | | Name | From | To | From | To |
| ISOMETRIC SYSTEM | | | | | | | |
| 4/m | $\bar{3}$ | 2/m | Normal | 0 | 45 | 0 | 55 |
| 4 | 3 | 2 | Plagiohedral | 0 | 90 | 0 | 55 |
| $\bar{4}$ | 3 | m | Tetrahedral | −45 | 45 | 0 | 55 |
| 2/m | $\bar{3}$ | | Pyritohedral | 0 | 90 | 0 | 55 |
| 2 | 3 | | Tetartohedral | −90 | 90 | 0 | 55 |
| HEXAGONAL SYSTEM | | | | | | | |
| 6/m | 2/m | 2/m | Normal | 0 | 30 | 0 | 90 |
| 6 | 2 | 2 | Trapezohedral | 0 | 60 | 0 | 90 |
| 6 | m | m | Hemimorphic | 0 | 30 | 0 | 180 |
| $\bar{6}$ | m | 2 | Trigonal | −30 | 30 | 0 | 90 |
| 6/m | | | Tripyramidal | 0 | 60 | 0 | 90 |
| 6 | | | Pyramidal-Hemimorphic | 0 | 60 | 0 | 180 |
| $\bar{6}$ | | | Trigonal-Tetartohedral | −60 | 60 | 0 | 90 |
| $\bar{3}$ | 2/m | | Rhombohedral | −30 | 30 | 0 | 90 |
| 3 | 2 | | Trapezohedral | 0 | 60 | 0 | 90 |
| 3 | m | | Rhombohedral-Hemimorphic | −30 | 30 | 0 | 180 |
| $\bar{3}$ | | | Tri-Rhombohedral | −60 | 60 | 0 | 90 |
| 3 | | | Trigonal-Tetartohedral-Hemimorphic | −60 | 60 | 0 | 180 |
| TETRAGONAL SYSTEM | | | | | | | |
| 4/m | 2/m | 2/m | Normal | 0 | 45 | 0 | 90 |
| 4 | 2 | 2 | Trapezohedral | −45 | 45 | 0 | 90 |
| 4 | m | m | Hemimorphic | 0 | 45 | 0 | 180 |
| $\bar{4}$ | 2 | m | Sphenoidal | −45 | 45 | 0 | 90 |
| 4/m | | | Tripyramidal | 0 | 90 | 0 | 90 |
| $\bar{4}$ | | | Tetartohedral | −90 | 90 | 0 | 90 |
| 4 | | | Pyramidal-Hemimorphic | 0 | 90 | 0 | 180 |
| ORTHORHOMBIC SYSTEM | | | | | | | |
| 2/m | 2/m | 2/m | Normal | 0 | 90 | 0 | 90 |
| 2 | 2 | 2 | Sphenoidal | −90 | 90 | 0 | 90 |
| 2 | m | m | Hemimorphic | 0 | 90 | 0 | 180 |
| MONOCLINIC SYSTEM | | | | | | | |
| 2/m | | | Normal | −90 | 90 | 0 | 90 |
| 2 | | | Hemimorphic | −180 | 180 | 0 | 90 |
| m | | | Clinohedral | −90 | 90 | 0 | 180 |
| TRICLINIC SYSTEM | | | | | | | |
| $\bar{1}$ | | | Normal | −180 | 180 | 0 | 90 |
| 1 | | | Asymmetric | −180 | 180 | 0 | 180 |

an easily applicable, fairly direct system of navigation in crystals. Other studies in which the technique might be useful would include problems of metallurgy and possibly of petrofabrics or mineral orientations in rocks.

### NAVIGATION IN CRYSTAL CORUNDUM

Just as the marine navigator must have charts of the bright stars in the sky, so the crystal navigator must have charts of the brightest "stars" in the x-ray diffraction patterns before him. Figure 5 is a stereographic projection showing one type of such chart for corundum—really a master chart of the entire crystal "sky," from which measurements may be made, and working charts prepared on the gnomonic projection. Every line or zone in Figure 5 represents a prominent line of spots in the x-ray pattern; every intersection represents a spot of marked brightness in the back-reflection Laue pattern.

Extensive navigational work is facilitated by the use of several gnomonic charts constructed from Figure 5, such as Figures 6 to 10. A gnomonic net (Fig. 11) and a back-reflection net (Fig. 12) serve for measuring "distances" between points in the projections.

The gnomonic charts (Figs. 6–10) are desirable for extensive work, for they help in distinguishing between pseudosymmetrical equivalents such as $c(0001)$ and $s(02\bar{2}1)$; $a(11\bar{2}0)$ and $R(01\bar{1}2)$; $p(11\bar{2}3)$ and $l(21\bar{3}1)$; and $q(20\bar{2}5)$, $n(22\bar{4}3)$, and $t(40\bar{4}1)$. The writer has constructed gnomonic charts centered on all these faces, and on $r(10\bar{1}1)$.

It is emphasized that a large collection of charts is justified only for an extensive program of navigation in crystals of lower symmetry. Similarly, calculated angle tables such as Table 1 are not essential since the desired angles can all be measured with sufficient accuracy on stereographic or gnomonic charts such as Figures 5 to 10, using either graphical constructions or a gnomonic net (Fig. 11).

Direct measurements between the principal "stars" in the back-reflection pattern are possible by means of Figure 12. This is a back-reflection net exactly analogous to the gnomonic net in Figure 11. Its use is essentially the same as that of Figure 11. The film is placed on Figure 12, and rotated about the common center until the two spots whose separation is desired fall on the same great-circle curve;—generally, this lies between two of the great-circle curves of the net, but its position can be estimated closely enough. The angular distance between the two spots can then be read off the chart, using the small circle curves as scale.

### NAVIGATION IN DIAMOND

Another example of practical crystal navigation is the necessity of controlling the orientation of diamond tools and dies. Since diamond is not the only material that crystallizes with a diamond-centered lattice, and since that lattice is also face-centered, charts which have been developed for use with diamond will serve with iron, copper, aluminum, and other materials that crystallize with lattices of these two types. Such master charts of the diamond "sky" are shown in Figures 13–15. In back-reflection Laue patterns of diamond, the following "stars" are usually brightest: $o\{111\}$, $d\{110\}$, $m\{311\}$, $a\{100\}$, $e\{210\}$, $V\{531\}$. By far the most conspicuous of these is $o\{111\}$; this "star" is bright, and it is the intersection point of the most prominent zones. The axial zones [100] are conspicuous by their faintness. An angle table for isometric crystals was published by Davey (1934, p. 509).

Majima and Togino (1927a) published a set of 55 master patterns of a face-cen-

tered cubic lattice, and another set of 55 for a body-centered lattice (1927b), made from forward-reflection Laue patterns of aluminum and iron crystals. The complexity of the forward-reflection Laue projection is illustrated by the number of patterns necessary to understandably cover all orientations of an isometric crystal. These authors made full use of the normal symmetry of the isometric system, but still considered a large number of patterns desirable for an adequate system of crystal navigation. In contrast, the writer's method has been used in connection with only three standard gnomonic projections (Figs. 13–15) for interpreting back-reflection Laue patterns of isometric diamond crystals, as described above. Actually, having attained a degree of manipulative skill, the writer and his associates rarely use even these three patterns, identifying the necessary points and zones directly on the film and reading the co-ordinate angle $\rho$ by means of the back-reflection scale marked on a Fisher projection protractor; $\theta$ is also measured directly by means of an ordinary protractor; but for accuracy a gnomonic sketch is required to obtain $\varphi$.

## DESIGN OF DIAMOND TOOLS

The following notes on diamond-tool design are appended herewith to further illustrate the importance of crystal navigation. Two major considerations control the design of a diamond tool. They are (1) weakness of the crystal due to cleavage, and (2) hardness variations which, in instances where cleavage is not important, may make large differences in the amount of acceptable work turned out for a given amount of tool wear. Kraus and Slawson (1941) recognized these two aspects of the problem. They emphasized the first in relation to diamond-die design and the second in relation to lathe tools. Further emphasis is here placed upon the great magnitude of the variations of wear resistance in diamond.

Whittaker (1944, p. 13) showed orientational hardness variations at least as great as 3 to 1 in wheel dressers. Since his work was not intended to test this factor, his ratio is probably a minimum. There is also a possibility that his scale was not uniform because many of the tests involved wearing away an appreciable volume of a pyramidal point which presumably offered varying resistance to wear as the surface area in contact with the grinding wheel increased. The larger variations measured by H. Winchell (1945) are not considered subject to the objections of variable pressure or area, for the quantity of diamond removed in any test was extremely small. These measurements were based on the number of units of production per polish. They show that the direction $[1\bar{1}0]$ on the surface (110) is of the order of 15 to 50 times as resistant to wear as [001] on (110); that $[\bar{1}\,\bar{1}2]$ on (111) is at least 100 times as resistant as [001] on (110); and that the direction on a given line may be very significant, as for example that $[\bar{1}\bar{1}3]$ on (332) is probably 30 to 80 times as resistant as $[11\bar{3}]$ on (332). It is emphasized again that these figures are orders of magnitude under certain arbitrary conditions. The conditions were held as nearly constant as possible, and the observations were repeated many times with only moderate variations; but since these are production figures obtained over a period of several years, no great accuracy is claimed for them. There is, however, a good qualitative agreement with the wear-resistance values reported by Peters *et al.* (1945). Thus there is no doubt that hardness in diamond varies greatly with orientation. Such variation necessitates careful

design of diamond tools, and crystal navigation is the only practical means for determining whether the designer's specifications have been met, and if not, what corrections must be made.

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# PETROGRAPHIC EXAMINATION OF CONCRETE AGGREGATES

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## ABSTRACT

Petrographic examination of concrete aggregates proposed for use on projects of the Bureau of Reclamation has assumed great importance as a supplement to standard, empirical, acceptance tests which are almost universally applied by large and progressive engineering organizations. Petrographic examinations entail visual inspection and lithologic segregation of various size-fractions of the aggregate, and they may be rapidly made by petrographers experienced in problems of concrete. Physical and chemical properties which are not determinable by any standard tests are estimated and qualitatively evaluated in terms of their effects upon concrete.

Methods employed and the point of view adopted in performance of the petrographic examination are discussed in this paper. Physical and chemical properties of aggregates which significantly affect concrete are outlined.

## INTRODUCTION

Concrete aggregates, which are usually composed of natural sands and gravels or of quarried rock, constitute the preponderant bulk of concrete (ranging, in general, from 80 to 85 per cent by weight), and they therefore have a marked effect upon strength, elasticity, durability, thermal properties, and unit weight of the concrete. Engineering organizations have long used empirical tests which were designed to supply data regarding the quality of aggregates and which serve as a basis for specifi-

cations controlling their acceptance (American Society for Testing Materials, 1944, p. 431–451). Experience has shown that the resulting data are statistically related to service histories of concrete containing the aggregates, but, in any given case, they may lead to incomplete or even erroneous conclusions (American Society for Testing Materials, 1943, p. 92–152).

All aggregates proposed for use on projects of the Bureau of Reclamation are tested in the Denver laboratories. Standard acceptance tests are always applied, but they are supplemented by petrographic examination performed by trained petrographers familiar also with problems of concrete. With passing time and increasing knowledge of the petrographic properties of aggregates, results of the examination have become progressively more meaningful, and increasing reliance has been placed upon them in acceptance or rejection of proposed materials. Because of the large number of aggregates investigated in the Bureau laboratories, the petrographic examination has been systematized for routine application. For example, between January 1 and September 1, 1945, 110 different concrete aggregates have been received and tested; the need for rapidity of determination and good judgment in estimating their physical and chemical qualities is apparent. Under such treatment, petrographic studies have contributed heavily to estimates of physical quality of these aggregates and have borne virtually the entire burden of diagnosis of their chemical suitability.

## ACKNOWLEDGMENTS

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## FACTORS AFFECTING QUALITY OF AGGREGATES

### GENERAL STATEMENT

The quality of concrete aggregate depends upon characteristics which influence serviceability of concrete. These characters affect concrete through both physical and chemical behavior. Therefore, adequate tests of aggregates must determine both the pertinent physical and the chemical properties. No detailed description of these properties will be given here, for their significance is fully discussed in a paper now in preparation. However, it should be noted that properties of aggregates may be due directly to typical characteristic of component rock types, or they may originate through secondary processes of alteration, erosion, or incrustation which may have modified them.

### PHYSICAL QUALITY OF AGGREGATES

Physical properties of aggregate which are most significant with regard to concrete are (1) abundance and nature of pores and internal fractures, (2) surface texture, (3) particle shape, (4) volume change with wetting and drying, and (5) coefficient of thermal expansion. Within the range expectable for most rocks, strength, elasticity,

compressibility, and thermal conductivity are not significant, except under special circumstances. Specific gravity of aggregate is significant where especially high or low unit weights are desired for the concrete; specific gravity is commonly used as an indication of porosity or permeability, but erroneous conclusions commonly result.

Although the five properties listed above control the physical quality of aggregate, none is directly determined by standard acceptance tests. On the other hand, data obtained from these tests become meaningful when they are correlated with results of petrographic examination; and therefore these data may be profitably used in connection with the petrographic study.

### CHEMICAL QUALITY OF AGGREGATES

Chemical properties of aggregates may affect service life of concrete in four ways: (1) Water-soluble substances may be leached out with attendant loss of strength and increase in porosity and may lead to development of efflorescence or scaling on the surface of the concrete (Schaffer, 1932, p. 56–60); (2) soluble constituents (Lea and Desch, 1935, p. 188, 217) or products of oxidation (Litehiser, 1938, p. 1) may retard or modify normal hydration of cement; (3) certain rocks and minerals react with high-alkali cements and may thus contribute to expansion and general deterioration of concrete (Blanks, 1943, p. 199–208); and (4) secondary minerals, such as zeolites, that are capable of base exchange in alkaline solutions, may release sodium or potassium which will aid attack on susceptible particles of the aggregate or which may produce efflorescence at the surface of the concrete.

Although special chemical tests may be applied under unusual circumstances, none of the acceptance tests ordinarily applied to aggregates is capable of detecting chemical properties which lead to the above effects on concrete. However, may rocks and minerals which possess such chemical properties are known and can be readily identified through petrographic examination. For example, the rocks and minerals known to react deleteriously with high-alkali cements are shown in Table 1.

Natural sands and gravels may be partially coated with any of several substances, which most commonly originate through precipitation from ground waters within the deposit. Such substances are commonly physically or chemically undesirable, and for this reason especial care must be exercised in their description and identification. Friable or loosely bonded coatings are physically deleterious; and other substances, such as gypsum or opal, may be chemically deleterious to concrete. In the experience of the Petrographic Laboratory, natural coatings have been observed to be composed of the following substances: silt, clay, gypsum, impure carbonates of lime and magnesia, opaline silica, manganese oxides, iron oxides, and mixtures of these materials. However, coatings which do not adversely affect either physical or chemical quality of the aggregate are not objectionable.

## PROCEDURE OF PETROGRAPHIC EXAMINATION

### COARSE AGGREGATES

Petrographic examination of coarse aggregates[1] has progressed from mere visual inspection to analyses through which compositions and properties of even complex

[1] Coarse aggregate includes that portion of the aggregate which is retained on the ¼-inch (No. 4) screen.

aggregates are described in detail. At the present time, the component rock types are identified and segregated into petrographic groups. Identification is accomplished by means of a hand lens, if adequate, or with binocular or petrographic microscopes.

TABLE 1.—*Rocks and minerals which are deleteriously reactive with high-alkali cements*

| Reactive Minerals | Chemical Composition | Physical Character |
|---|---|---|
| Opal | $SiO_2 \cdot nH_2O$ | Amorphous |
| Chalcedony | $SiO_2$ | Cryptocrystalline fibrous |
| Tridymite* | $SiO_2$ | Crystalline |

| Reactive Rocks† | Reactive Component |
|---|---|
| Siliceous Rocks: | |
| Opaline cherts | Opal |
| Chalcedonic cherts | Chalcedony |
| Siliceous limestones | Chalcedony and/or opal |
| Volcanic Rocks**: | |
| Rhyolites and rhyolite tuffs | Volcanic glass, devitrified glass, and tridymite |
| Dacites and dacite tuffs | |
| Andesites and andesite tuffs | |
| Metamorphic Rocks: | |
| Phyllites | Hydromica (?) |
| Miscellaneous Rocks: | |
| Any rocks containing veinlets, inclusions, or grains of the reactive rocks or minerals listed above. | |

* Hornibrook *et al.*, 1943, p. 218.
† Artificial silicate glasses, such as pyrex glass, are known to be deleteriously reactive.
** The volcanic types listed are known to be deleteriously reactive; basalts are known to be innocuous; data regarding trachytes, latites, and phonolites are lacking.

Experience has shown that studies of coarse aggregates may be adequate if only the 1½- to ¾-inch and ¾- to ⅜-inch size fractions are analyzed in detail, and the other size fractions then merely qualitatively compared with them. In general, samples received from the field do not contain a sufficient quantity of aggregate retained on the 1½-inch screen for satisfactory statistical treatment, and gravel passing the ⅜-inch screen is so fine as to make reliable analyses very slow and laborious. However, detailed analyses of any size fraction may be warranted by (1) significant lithologic or physical differences in various sizes of aggregate, (2) presence of varying proportions of deleterious materials in different size fractions, or (3) absence of sufficient gravel of the 1½- to ⅜-inch fractions. Partial analyses, involving merely segregation of particles of particular significance, may be made of any gravel fraction or of coarse fractions of the sand.

Segregation of the lithologic groups is based not alone on petrographic classification, but also upon physical and chemical properties. Thus, granites may be segregated into several groups depending upon characteristics of the particles. For

example, weathered or fractured particles may adversely affect the quality of concrete containing them, and so they must be distinquished from particles of granite which are fresh and sound. Other rock types, which fall into the same petrographic class, may be segregated into either chemically innocuous or deleterious groups, depending upon presence or absence of certain minor constituents. Thus, andesite porphyries may be innocuous or deleterious according to abundance of natural glass, opal, chalcedony, or other chemically unstable materials.

### FINE AGGREGATES

Fine aggregates comprise materials which pass the $\frac{3}{16}$-inch (No. 4) screen. They are not usually segregated into lithologic groups during petrographic examination since the time necessary for reliable analyses is very great and out of proportion to the information gained. However, abundance of innocuous and physically sound ingredients is estimated, and the proportions of deleterious or physically unsound substances are determined. Variations in lithology and quality with grain size are discussed in a report summarizing results of the petrographic study.

## STANDARD TESTS AND PETROGRAPHIC EXAMINATION

With the exception of the test for organic materials in sand (American Society for Testing Materials, 1944, p. 438), deficiencies of which have been described (Paul, 1939, p. 892–897), none of the standard acceptance tests of concrete aggregates (American Society for Testing Materials, 1944, p. 431–451) yield data relative to their chemical suitability. These physical tests are designed to measure specific gravity; water absorption; structural strength; soundness under conditions of freezing and thawing; quantity of such substances as coal, clay lumps, and shale; and abrasive resistance of aggregates. Specific gravity and water absorption are measured simultaneously. Structural strength of fine aggregates is determined indirectly through measurement of compressive strength of standard mortars containing the aggregates. Soundness is measured by means of the sulfate crystallization test[2] or by actual freezing and thawing of immersed aggregates. Coal and shale are determined by flotation in heavy liquids, whereas particles which can be broken between the fingers into finely divided fragments are classified as clay lumps. Abrasive resistance is commonly measured in the Los Angeles abrasion machine (American Society for Testing Materials, 1944, p. 431–433), which comprises a rotating drum containing the sample of aggregate together with standardized steel balls; breakdown of the aggregate is due principally to impact of the balls rather than to abrasion (American Society for Testing Materials, 1943, p. 125).

[2] The so-called crystallization test involves immersion of carefully screened samples of aggregate in a saturated solution of either sodium or magnesium sulfate (American Society for Testing Materials, 1944, p. 1332). After a fixed period of time, the samples are removed from the solution, drained, and oven-dried. They are then cooled and reimmersed to begin the second cycle. Acceptance specifications generally require 5 or 10 cycles of the test. Breakdown of the aggregate is measured as material which passes the screen upon which the sample was retained prior to testing. During the oven drying, crystals of $Na_2SO_4$ or $MgSO_4 \cdot H_2O$ are precipitated in pores of the aggregate particles; and these crystals may virtually fill some pores after several cycles of the test. Upon reimmersion of the aggregate, the precipitated crystals hydrate to $Na_2SO_4 \cdot 10H_2O$ or $MgSO_4 \cdot 7H_2O$. It is generally believed that the resultant expansion of the crystals may create stresses which may rupture the walls of the pores, and thus cause physical breakdown of unsound materials. For additional discussion of the tests see Garrity and Kriege (1935, p. 237–258).

Petrographic examination of aggregates may be used independently or as a supplement to standard acceptance tests. Thus, breakdown in the sodium-sulfate soundness test of a phyllite aggregate proposed for use at Fontana Dam was revealed only by visual examination of the sample, for the flat particles produced by disintegration did not pass the screen at completion of the test. Specifications governing the lower limit of specific gravity of aggregates are commonly used to prevent acceptance of materials which contain significant proportions of soft, porous, or weathered substances. Several natural aggregates from near Provo, Utah, with very low specific gravity could have been rejected on the basis of this specification, but petrographic examination showed the low specific gravity to be due to firm or hard but porous sandstones. These aggregates were recommended for use.

Petrographic examination of aggregates may reveal deficiencies requiring special tests. For example, a quarried gabbro from Yamhill Project, Oregon, passed all acceptance tests for soundness, but microscopic examination of the rock showed that a claylike alteration product occurred interstitially in large quantities. Special tests proved the rock to be susceptible to large volume changes with wetting and drying; and concrete beams containing the crushed gabbro as aggregate were characterized by excessive drying shrinkage and very low freezing and thawing durability. The quarry was rejected as a source for concrete aggregate. Chemically unstable minerals are not detected by standard tests; petrographic examination is the only practicable, routine method by which such deleterious substances as gypsum, sulfides, or alkali-reactive compounds may be discovered. In this way, coatings of gypsum were identified on natural aggregate proposed for use at Boulder Canyon Project; and as a result plant-processing methods which efficiently removed the gypsum were designed.

Petrographic examination permits classification of aggregates, and results of laboratory tests or service histories are then applicable to other aggregates of similar lithology. On the other hand, tests and service records on an aggregate which is not so classified are significant only with regard to concretes containing that aggregate.

## PETROGRAPHIC CHARACTER AND ANTICIPATED SERVICE

Correlation of petrographic character with effects of aggregates upon concrete is not complete, but some advance has been made in this direction. The suitability of an aggregate is established when the material is known to have produced satisfactory concrete under a variety of environmental conditions. Similarly, laboratory tests of concretes may yield information regarding the quality of aggregate. Through comparison of service histories and results of laboratory tests of concretes with petrographic character of the aggregates, many specific properties of aggregates have been approximately correlated with quality of concrete under different conditions of service. Petrographic study and classification of aggregates whose physical and chemical suitabilities are known permit accurate diagnosis of new aggregates which are lithologically similar. For example, poor bonding characteristics of some very coarse-grained granitic aggregates in the Rocky Mountain region have been observed to induce freezing and thawing breakdown of concrete. New aggregates of similar

type are regarded as inferior, but yet the particular property leading to this decision is not revealed by any standard acceptance tests. In this same way, potential reactivity of aggregate with alkalies in cement may be predicted with considerable accuracy.

## REPORTING THE PETROGRAPHIC EXAMINATION

Reports describing petrographic examination of proposed aggregates include tables which summarize analyses of coarse fractions. Actual percentages of each rock type are recorded, and brief descriptions are included. Each petrographic type is classified as to physical and chemical quality (Table 2). The physical and chemical quality of the coarse aggregate is summarized in a separate table (Table 3). Degrees of physical quality are "good," "satisfactory," "fair," and "poor"; degrees of chemical quality are "innocuous" and "deleterious." These words are defined as follows:

"Deleterious" materials are capable of producing adverse effects on concrete through chemical reactions which take place after hardening of the cement. Constituents designated as "deleterious" because of susceptibility to attack by alkalies in cement generally do not yield to reaction if the cement contains less than 0.60 per cent total alkalies ($Na_2O$ plus $K_2O$, expressed as soda equivalents).

"Innocuous" constituents do not participate in chemical reactions harmful to concrete.

"Good" aggregate constituents contribute to superior strength, abrasive resistance, and durability of concrete under any climatic conditions.

"Satisfactory" aggregate constituents contribute to high or moderate strength, abrasive resistance, and durability of concrete under any climatic conditions.

"Fair" aggregate constituents contribute to moderate strength and abrasive resistance of concrete, but under rigorous climatic conditions they contribute to physical breakdown of concrete.

"Poor" aggregate constituents contribute to low strength and abrasive resistance of concrete under any climatic conditions and cause physical breakdown of concrete under rigorous climatic conditions.

Ordinarily, characteristics of sands are not tabulated but are described in the text of the report, inasmuch as quantitative analyses, amenable to tabular presentation, are made of sands only under special circumstances.

The descriptive data in the report are always followed by specific conclusions and recommendations regarding use of the aggregate.

## STATEMENT OF QUALITY

### GENERAL DISCUSSION

Either of two concepts may be used as a basis for an appraisal of aggregate quality. One concept considers aggregates from the point of view of a local user, and all environmental aspects of the situation in which the aggregate is to be used are integrated into a statement of quality. This concept may be called the "specific-

TABLE 2.—*Petrographic analyses of coarse aggregate*

Deposit No. 3, Tract 80 and Lot 74, Sec. 35, T. 53 N., R. 102 W. Approximately 2 miles west of Cody, Wyoming. Proposed for use in Heart Mountain Powerhouse, Heart Mountain Division, Shoshone Project.

| Rock Types | Per cent by Weight | | Descriptions of the Rock Types | Quality | |
|---|---|---|---|---|---|
| | 1½"–¾" | ¾"–¼" | | Physical | Chemical |
| Diorites and diorite porphyries | 11.9 | 8.9 | Slightly to moderately weathered, fine-grained, massive. | Satisfactory | Innocuous |
| Granophyres | 0.3 | | Slightly weathered, massive, aphanitic, reddish | Good | Deleterious |
| Intermediate volcanic rocks | 16.4 | 13.0 | Slightly to moderately weathered, massive to vesicular, aphanitic, commonly zeolitic | Good | Deleterious |
| Basic volcanic rocks | 58.6 | 64.4 | Slightly to moderately weathered, aphanitic, massive to vesicular, typically olivine bearing and zeolitic | Satisfactory | Innocuous* |
| Weathered basic volcanic rocks | 6.5 | 10.0 | Moderately weathered, fractured to firm, aphanitic, typically olivine bearing and zeolitic | Fair | Innocuous* |
| Intermediate tuffs | 5.0 | 1.5 | Slightly to moderately weathered, hard, massive, lithic tuffs | Satisfactory | Deleterious |
| Limestones | 1.0 | 1.9 | Hard, massive, finely crystalline, pure | Satisfactory | Innocuous |
| Weathered siliceous limestones | 0.3 | 0.3 | Hard to firm, porous | Poor | Deleterious |

* Rare facies contain small amounts of opal in void spaces.

TABLE 3.—*Petrographic analyses of coarse aggregate for quality*

Deposit No. 3, Tract 80 and Lot 74, Sec. 35, T. 53 N., R. 102 W. Approximately 2 miles west of Cody, Wyoming. Proposed for use in Heart Mountain Powerhouse, Heart Mountain Division, Shoshone Project.

| Degrees of Quality | Per cent by Weight | |
|---|---|---|
| | 1½"–¾" | ¾"–¼" |
| Good | 16.7 | 13.0 |
| Satisfactory | 76.5 | 76.7 |
| Fair | 6.5 | 10.0 |
| Poor | 0.3 | 0.3 |
| Innocuous | 78.0 | 85.2 |
| Deleterious (with high-alkali cements) | 22.0 | 14.8 |

service" point of view. On the other hand, aggregates may be compared with some absolute standard and classified without regard to anticipated conditions of service.

This concept may be called the "standard-basis" point of view. Merits of these two concepts in study of aggregates are briefly discussed below.

### "SPECIFIC-SERVICE" POINT OF VIEW

Under the specific-service point of view, a user is interested in serviceability of an aggregate under conditions encountered at a particular job. Thus, he is little concerned with freezing and thawing durability in an area where freezing temperatures are rarely experienced. For this type of study, environmental conditions of service must always be kept in mind by an investigator, in order that each property of an aggregate may be correlated with these conditions *before the quality of the aggregate receives a designation.* That is, a certain rock type may be characterized by a property which leads directly to low freezing and thawing durability; in an area of rigorous climate, this rock type will be considered inferior in quality. However, in a region of mild climate, it may be entirely suitable for use.

There are two objections to this type of study. (1) Subjective elements involved in description of the aggregate are combined with the highly subjective integration of aggregate properties and environment, and (2) identical aggregates to be used under different conditions of service will be classified according to an entirely different scale of quality.

### "STANDARD-BASIS" POINT OF VIEW

Laboratory routines of aggregate testing are simplified if the properties are classified according to some absolute standard, with a minimum of interpretation. This method is the basic concept behind standard acceptance tests, such as the sodium-sulfate soundness test. These tests yield certain results regardless of conditions under which the aggregate is expected to serve. Then, as an entirely separate step in the investigation, these results are correlated with the conditions of service, and an appropriate recommendation is made regarding suitability of the aggregate.

This general concept is followed by the Petrographic Laboratory in examination of concrete aggregates, and definitions of the degrees of quality have been formulated under this point of view. Identical aggregates have identical analyses, in spite of the fact that one might be used in a rigorous, and the other in a mild climate. However, as a separate step, quality of the aggregate is subsequently correlated with anticipated conditions of service in order that specific recommendations as to suitability can be made.

### JUDGMENT IN SELECTION OF AGGREGATES

Application of petrography to selection of concrete aggregates requires considerable interpretation by the petrographer, and thus value of the study will be strongly colored by his individual ability and experience. It is desirable that the subjective element be kept to a minimum in any investigation; on this account, a meticulously factual basis is to be sought in petrographic analysis of aggregates. Thus far, however, no completely objective basis for selecting concrete aggregates has been devised. It is obvious that standard acceptance tests, although inadequate, are, in themselves, essentially objective, and that no personal element enters into their

results so long as specified procedures are followed. On the other hand, highly subjective judgments are involved in interpretation of the test results, and in appraisal of these results relative to effects of the aggregate upon concrete under anticipated conditions of service. Thus, ultimate recommendations for acceptance or rejection of concrete aggregates are necessarily based largely upon judgment, regardless of the method used.

## CONCLUSIONS

Petrographic examination contributes significantly to efficacy of selection of concrete aggregates. When conducted by petrographers experienced in problems of concrete, such examinations yield information regarding physical and chemical quality of aggregates which is obtainable in no other way on a practicable and routine basis. They supplement standard acceptance tests designed to reveal physical quality of proposed aggregates; but, on the other hand, visual examination is the only technique by which chemically deleterious rocks and minerals are detected.

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# PROGRESS IN PALEONTOLOGICAL RESEARCH ON THE PACIFIC COAST, 1917–1944

BY CHESTER STOCK

(*Address as Retiring President of the Paleontological Society*)

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## INTRODUCTORY STATEMENT

More than a quarter of a century has elapsed since last a report of this kind was presented before the general assembly of the Paleontological Society. The annual presidential address, entitled: *An outline of progress in palaeontological research on the Pacific Coast*, given before the Society in 1917 by my distinguished predecessor, the late Dr. John C. Merriam (Vertebrate Paleontology, 1921), gave an account of the early period of exploratory work and research, and reviewed particularly what had been accomplished during the span of time measured by his active participation while resident professor at the University of California.

The present, therefore, seems a fitting occasion to determine in retrospect the state of well-being of our science on the West Coast, and to take stock, so to speak, of its accomplishments since the last review. It seems appropriate to ascertain from such acquisitions to knowledge what trends, if any, have developed in paleontology, and, for the benefit of those who contemplate engaging in this discipline, what the expectancy is of continued healthy and vigorous growth of their chosen science. For, while many may shrink from a contemplation of paleontology as a decadent discipline, yea, vehemently oppose the mere thought of such an eventuality, it is,

nevertheless, true that individual fields of investigation ultimately are drained of their major values or, at least, reach a stage of diminishing return where the research products obtained are no longer commensurate to the time and effort expended. Perhaps in a historical science like paleontology the need for small increments of knowledge will always be great, since the larger the number of these the clearer become the actors and the scenes in the ever-changing drama of life. While the constant repetition of old procedures and techniques may not be conducive to striking new departures of thought, it is impossible to foretell when an isolated fact, buried in the stock pile of a science, contemplated anew, becomes the focal point whence an avenue of research reaches out in a new direction.

The present era has seen an expansion in paleontological fact and thought, and no major subdivision of the science may be said to have languished. Indeed, it is a source of much satisfaction to realize that while the older traditions and the men chiefly responsible for them receive due reverence and respect, in no wise have the former served as deterrents to new departures.

## MICROPALEONTOLOGY

This discipline represents the most striking new development in paleontology in the era under review. Although fossil diatoms formed the basis of the earliest paleontological studies of materials collected on the West Coast, and a few papers relating to ostracods and Foraminifera appeared in the early years of the present century, it was not until 1917 that micropaleontology began its real growth as a science in America. Impetus to a rapid and robust development was given by the petroleum industry, once its significance as an applied science was fully appreciated. Its application to problems of age and correlation of strata in the petroleum-producing areas of California occurred inauspiciously during the early twenties.

The earliest worker in micropaleontology to publish the results of his research was G. Dallas Hanna, who in 1923 made a study of the sediments near Lomita and, in another paper, directed attention to the Eocene Foraminifera found near Vacaville, California. In the following year he discussed the significance of the smaller Foraminifera to stratigraphy.

Meanwhile, Cushman, whose interest turned so completely to foraminiferal research in the years immediately preceding the twenties, had published a number of papers describing Recent and fossil Foraminifera. Among the first of a long list of contributions from the Cushman laboratory are papers in which Tertiary Foraminifera are described from California and, somewhat later, from Oregon as well. As frequently happens in the beginning stages of a biological science the emphasis in those early contributions was placed on classification and nomenclature. These aspects of the subject still claim considerable attention, largely because of the nature of the fossil material.

One of the early comprehensive studies of a foraminiferal fauna was by Galloway and Wissler (1927) on a Pleistocene assemblage obtained in the Lomita Quarry of the Palos Verdes Hills. It is interesting to note that the paper was published in the first volume of the Journal of Paleontology, issued in 1927, by the newly formed

Society of Economic Paleontologists and Mineralogists. In the same volume appeared four additional articles dealing with diatoms, Foraminifera, and silicoflagellates from California by G. D. Hanna, Hanna and Church, and Church. In this year, also, Schenck (1927) directed attention to the occurrence of diatoms in shales of western Oregon. Pliocene brackish-water diatoms from California were described by Hanna and Grant (1929), and Miocene forms were recorded from the Temblor of the famous Shark-tooth Hill locality in Kern County (Hanna, 1932). In view of the many occurrences of diatomaceous earth in the west, it seems strange that so few published accounts of fossil diatoms have appeared. Additional reports on foraminiferal assemblages from particular areas in California were published in 1927 by Cushman and Marcus Hanna, Cushman and G. Dallas Hanna, and Cushman and Grant. These appeared in the Transactions of the San Diego Society of Natural History and in the Proceedings of the California Academy of Sciences.

From the beginnings here outlined has come a constantly growing appreciation of the fundamental worth of foraminiferal studies. Their intrinsic value to the petroleum geologist, as well as the economic demand, are largely responsible for the fact that in this field the lead has been wrested from workers in academies, museums, and universities and resides now in the micropaleontological laboratories of the major oil companies, and to a lesser extent with commercial micropaleontologists. These laboratories hold a unique position in the field of paleontology. Their staffs of trained and competent observers are keenly aware of the value of the multitudinous data to the oil industry. While the dissemination of this knowledge is sometimes limited to the select few, opportunities are not lacking to make the information available in printed form for wider appraisal.

The literature on fossil Foraminifera is extensive and in total bulk exceeds that on all other micro-organisms combined. While purely descriptive work is done from time to time, chiefly by Cushman and collaborators (*see also:* R. E. and K. C. Stewart, 1930; Barbat and Johnson 1934; Berthiaume, 1938), interest is largely in problems requiring detailed zonation and correlation, or in biostratigraphy and ecology. A general discussion of the relation of the Foraminifera to zonal paleontology was published by Adams (1939). A recent example of the application of micropaleontological evidence to stratigraphy is the excellent contribution to the geology of the Los Angeles Basin oil fields by S. G. Wissler (1941). Of similar importance are the contributions of a score or more of micropaleontologists who have contributed to an understanding of microfaunal zones and stratigraphy in active and potential oil-producing regions (Barbat and Von Estorff, 1933; Goudkoff, 1926; Laiming, 1939; 1940). Noteworthy papers have appeared which deal with specific kinds of Foraminifera and their significance as horizon markers or as indicators of age (Woodring, 1930; 1931; Taliaferro and Schenck, 1933, Schenck and Childs, 1942). Some study has been made of the internal structure of Foraminifera, particularly of the larger forms (Schenck and Aguerrevere, 1926; Schenck and Childs, 1942; Schenck, 1944). At present the bulk of foraminiferal research relates to the Tertiary, and only occasional reports on Cretaceous microfaunas are published (Cushman and collaborators, 1929; 1935). As the geographic horizon of micropaleontological investigation widens, further noteworthy publications from Pacific Coast workers,

like that of Beck (1943) on the Cowlitz Eocene Foraminifera of Washington, may be expected.

Marking a constructive step forward is the important work by R. M. Kleinpell, published in 1938. This book marshals a large quantity of data and furnishes a systematic catalogue of Miocene Foraminifera. Among its broad contributions are: (1) formulation of the time-stratigraphic concept for the Californian region based on the Foraminifera, (2) recognition of a succession of foraminiferal stages for the Miocene, and (3) introduction of stage names that have received wide acceptance among micropaleontologists on the Pacific Coast. The ecology of some fossil and Recent Foraminifera has been discussed by Natland (1933). Important microfaunal and biostratigraphic studies were made by Schenck. Students trained by him and the contributions from his laboratory make Stanford University the outstanding academic institution on the Pacific Coast where micropaleontological research is conducted. Schenck, Keen, and Martin (1940) gave an interesting summary of the development of micropaleontology in California. Later in the same year Schenck reviewed the broad field of applied paleontology, discussing the values of the science, its objectives, and methods of correlation. In the conclusion to his paper Schenck directs attention to the many authors who are contributors to the subject of the practical use of fossils, among whom California micropaleontologists and geologists are well represented (Tolman, 1929; Schenk, 1932; Camp and Hanna, 1937; Schenck and White, 1942). Still more recently, Schenck and Adams (1943) made an interesting survey of the operations of commercial micropaleontological laboratories. Since 1933 very helpful bibliographies on the Foraminifera have been published annually by Hans Thalmann (1933—).

The report on Eocene radiolarian faunas from the Mt. Diablo area, California, by Clark and Campbell (1942), and that on Miocene radiolarian faunas from southern California by the same authors (Campbell and Clark, 1944) present the results of studies of new and strikingly well preserved materials. The pioneering work of these investigators sheds most welcome light on a group of organisms whose fossil representatives are little known. While the value of Radiolaria in correlation remains to be tested with acquisition of additional faunas, their contribution to marine paleoecology is well demonstrated by the authors.

## INVERTEBRATE PALEONTOLOGY

A discovery of considerable interest announced by Hinds (1938) is that of the occurrence of a jellyfish in Algonkian rocks of the Grand Canyon of the Colorado. There remains, however, a great dearth of paleontological information relating to pre-Mesozoic time in California and the Northwest. Very little systematic work has been done on the invertebrates of the Paleozoic. Since fossils are known to occur in Paleozoic horizons and since the strata are sometimes thick and well represented, this era presents one of the more promising fields for future research.

Collections of Cambrian fossils are still poor in species, and no monographic studies of Cambrian faunas have yet been undertaken. C. W. Clark (1921) published a brief account of lower and middle Cambrian formations of the Mohave Desert in

which he listed the fossils from the two horizons. This material was later reported upon by Resser (1928). In 1933, Hazzard discussed the rocks and paleontology of the Cambrian in the eastern Mohave Desert. In the same year, Phleger (1933) published descriptions of some Ordovician fossils from the Inyo Range. Three years later Hazzard and Mason (1936) discussed the middle Cambrian formations of the Providence and Marble mountains, California. Mason (1935) described a Cambrian fauna from the latter range. The important stratigraphic studies of Hazzard (1937) in the vicinity of Death Valley yielded fossil materials on which the ages of the periods of the Paleozoic were determined by Kirk and Cooper, and J. F. Mason.

Devonian fossil assemblages from California were discussed by Stauffer (1930). Somewhat different views with reference to the Californian Devonian were expressed by C. W. Merriam (1940) in his excellent contribution to the Devonian paleontology of the Roberts Mountains region, Nevada.

The studies of J. P. Smith on the stratigraphy and geologic history of the Cephalopoda of the late Paleozoic and early Mesozoic were concluded with publication (Smith, 1927) of the monograph on the Upper Triassic invertebrate faunas of North America, and that (Smith, 1932) on the lower Triassic ammonoids of North America. These publications are fundamental in scope and will long remain the basis for any future work in this field of investigation. Some new Lower Karnic ammonoids were described from New Pass, Nevada, by Johnston (1941). No further interest seems to be displayed in tracing the phylogenetic development of particular strains or races among the Ammonoidea. Muller and Ferguson (1936), as a result of geologic studies in west-central Nevada, gave an account of the Triassic and Jurassic deposits with lists of fossils from individual formations.

Contributions to Jurassic paleontology have been made by Crickmay (1927-1933), Packard (1921), Lupher and Packard (1930), and others, but the advance of knowledge in this field has not been so great as that concerning the Triassic.

Study of Cretaceous faunas suffered almost a similar fate, but in recent years there has been a resurgence of interest, not altogether accounted for by a growing interest in the rocks of this period by the petroleum industry. Packard (1922) described new Cretaceous fossils from the Santa Ana Mountains. Important additions to the knowledge of Cretaceous molluscan assemblages are the results of research by Popenoe (1937; 1942; 1943). Additions to Cretaceous paleontology were made also by Anderson (1931a). These facts are being utilized in an attempt to establish the correct succession of faunas for the period on the Pacific Coast.

The major activities of invertebrate paleontologists on the Pacific Coast continue to be in the marine Tertiary. Earlier work had been reviewed by Clark (1921a; 1921b) in his discussions of the relationships of the middle Eocene faunas of California and the marine Tertiary of the Pacific Coast with relation to its sequence, paleogeography, and problems of correlation. Valuable services were rendered by Stewart (1927; 1930) in establishing the types in the early paleontological collections from California that had been studied by Gabb. These papers by Stewart contain much information, and his discussions of problems of nomenclature raised by this review are of interest to the systematist. Further studies of molluscan

faunas by Trask (1922), Wagner and Schilling (1923), Palmer (1923), Nelson (1925), Clark (1926), Clark and Woodford (1927), G. D. Hanna (1926), Waterfall (1929), Loel and Corey (1932), and Merriam and Turner (1937) added a vast amount of paleontologic data concerning many stages of Tertiary time. These researches were pursued in the Californian area. Similar investigations were undertaken in the Northwest. Among the contributions to paleontology are those by Howe (1922), Clark, Arnold, and Vaughan (1923), Clark (1924), Etherington (1931), Tegland (1933), Effinger (1938), and Turner (1938). These relate for the most part to faunas from the lower Tertiary.

In addition, individual groups of invertebrates received special study. Thus, for the Mollusca particular mention should be made of the carefully executed research on the genus *Acila* by Schenck (1936) and on the Turritellas by C. W. Merriam (1941). Other studies furnishing valuable information are those on a revision of the *Rimmela*-like gastropods by Clark and Palmer (Clark, 1923), on *Venericardia* by Marcus Hanna (1925), on the Cassididae by Schenck (1926), on *Pitaria* by Tegland (1929), on *Galeodea* by Tegland (1931) and Durham (1942), on *Velates* by Vokes (1935), on the Epitoniidae by Durham (1937), and on *Exilia* by Bentson (1940). The number of contributors is in itself a striking expression of the sustaining interest in this field of research, much of which is due to the guiding spirit and contagious enthusiasm of the late Bruce L. Clark.

Nor does this exhaust the list of publications on Tertiary Mollusca. Clark and Vokes (1936) summarized the information relating to the marine Eocene sequence, and in a later paper Clark (1942) pointed out the close resemblance between certain Eocene gastropods of California and comparable species known from western Europe. Reinhart (1937) discussed certain Cretaceous and Tertiary pelecypods that had been incorrectly assigned to the Arcidae.

For many years the Colorado Desert has claimed the attention of paleontologists because of the intriguing marine history recorded there, especially in its relation to that of the Gulf of Lower California. G. D. Hanna (1926) reported on the paleontology of Coyote Mountain, while a fuller statement of the distribution and age of the marine Tertiary deposits in this region was made by Woodring (1932). The expeditions of the California Academy of Sciences to Lower California and adjacent areas brought to light later Tertiary assemblages described in a series of papers by Hertlein (1925), Jordan (1926), Jordan and Hertlein (1926), Hertlein and Jordan (1927), and by G. D. Hanna and Hertlein (1927). Hertlein (1928) reported on the paleontology of the Channel Islands, California. Woodring also called attention to the occurrence of Vaqueros fossils on the north side of the San Andreas rift in Cajon Pass.

Excellent stratigraphical and faunal studies of particular areas in California have been made by members of the U. S. Geological Survey. The contributions by Woodring, Stewart, and Richards (1940) on the Kettleman Hills, and by Woodring, Bramlette, and Kew (in press; *see also* Woodring, Bramlette, and Kleinpell, 1936) on the Palos Verdes Hills, are achievements that reflect the best traditions of the Federal survey.

Hertlein and Crickmay (1925) published a summary statement of the nomen-

clature and stratigraphy of the marine Tertiary of Oregon and Washington. Charles E. Weaver has continued his studies of the stratigraphy and Tertiary paleontology of Washington from the earlier period. Thus, new fossil mollusks from the Eocene formation of Washington were described by Weaver and Palmer (1922). Later, Weaver (1937) discussed the Tertiary stratigraphy of western Washington and northwestern Oregon. A useful compendium of the paleontology of the marine Tertiary of Oregon and Washington, with comments on individual species by the author, is the most recent work of Weaver (1942) relating to this region.

A large number of descriptive papers dealing with the later Pliocene and particularly the Pleistocene Mollusca of California have appeared (Grant and Strong, 1934; Oldroyd, 1924; Webb, 1937; Willett, 1937; Woodring, 1935). Probably the most enterprising of these is the catalogue of Pliocene and Pleistocene Mollusca by Grant and Gale (1931); these authors also discuss morphology, classification, nomenclature, and stratigraphy. In a consideration of the later Tertiary and Pleistocene faunas, a promising field awaiting further cultivation is paleoecology (Woodring, 1935; 1938; Vokes, 1939). A need of guides to the characteristic molluscan fossils of the Tertiary and Pleistocene has been met by the publications of Clark (*ca.* 1924), Schenck and Keen (1940), and by G. D. Hanna and Hertlein (1941). This last paper illustrates also some of the characteristic diatoms and Foraminifera.

Few students have interested themselves in fresh-water and land shells of the Mesozoic and Cenozoic. McNeil (1939) described fresh-water invertebrates from deposits of Cretaceous age at Eureka, Nevada. Fossil land shells from the John Day Basin, Oregon, were described by G. D. Hanna (1920), and the same author (Hanna, 1922) reported on Tertiary and Pleistocene fresh-water mollusks from Oregon. Miocene lacustrine shells from Sonoma County, California, were recorded by Hanna (1923). Probably the most extended study is that by Pilsbry (1935) on the Pliocene Mollusca from the Tulare and San Joaquin formations of the Kettleman Hills. Short contributions on fossil land snails, ranging in age from Eocene to Pleistocene, have been published by G. D. Hanna (1934; 1936).

Fossil chitons of the Pacific Coast have been studied, almost exclusively, by Berry (1922). With the exception of the investigations by J. P. Smith, the most noteworthy contribution to the literature on fossil Cephalopoda of the West Coast is that on the nautiloid genus *Aturia* by Schenck (1931). Anderson (1931b) discussed the genus *Fagesia* in the Upper Cretaceous. A comprehensive and very useful account of the Cenozoic brachiopods of western North America has been published recently by Hertlein and Grant (1944). Relatively few papers have appeared which deal with fossil corals. This group probably deserves more intensive study than has been its lot during the past 2 decades. The rugose corals from the Upper Devonian Nevada limestone were recorded by Stum (1940), while the Carboniferous and Permian corals were described from central Oregon by C. W. Merriam (1942). Durham (1941; 1942) published on a new Pliocene coral from California, and on Eocene and Oligocene coral faunas from Washington.

The fossil Echinoidea have received some attention. Supplementing the earlier work by Kew is a descriptive paper by Israelsky (1923). The unusual occurrence of a brittle-star limestone was discussed by C. W. Merriam (1931). Seven years

later, Grant and Hertlein (1938) reviewed the West Coast Cenozoic Echinoidea. The paper is a catalogue of known types, with a revision of some of the genera and species, and includes data on new localities. Woodring (1938) recorded an interesting deep-water echinoid (echinothuriid) from the Repetto formation of the Los Angeles basin. Eaton, Grant, and Allen (1941) figured and briefly described a plethora of species of the genus *Astrodapsis*. These forms occur in successive horizons ranging upward in age from Lower Briones to Lower Neroly in the Miocene section of Caliente Mountain. Aside from this local history of a particular subdivision of the Echinoidea, no further attempt has been made to outline the phylogenetic development of the group, insofar as this is suggested by the fossil record on the Pacific Coast. The most significant addition to the knowledge of fossil Crustacea from the west is that by Rathbun (1926). Most of the specimens described by Miss Rathbun represent crabs from the Cretaceous and the several epochs of the Cenozoic. Tertiary fresh-water crayfish are likewise described from Oregon and Idaho.

A recent summary of the correlation of marine Cenozoic formations of western North America was published by a subcommittee of the Committee on Stratigraphy of the National Research Council (Weaver *et al.*, 1944).

Very little information has become available concerning fossil insects. Much of what is known relates to those forms recovered from the Pleistocene asphalt deposits of southern California and from cave accumulations in the northern part of the State, and is the result of studies by Fordyce Grinnell during the earlier period. The list of insects from Rancho La Brea was subsequently revised, and later Essig (1931) identified some additional species from this locality. Essig, likewise, identified some large dragonflies and Coleoptera from the McKittrick asphalt and directed attention to the presence of fossil insects in the brea of Carpinteria. The oldest known insect from California is an extinct genus of dragonfly described by Cockerell (1930) from Eocene rocks in Shasta County. More than a decade elapsed before another paper appeared which dealt with fossil Insecta. Recently, Pierce (1944) recorded descriptions of fragmentary remains of carabid beetles from the Lower Miocene (Saucesian) of San Luis Obispo and Kern counties, California. These specimens are referred to *Bembidion*, an existing genus which is recognized in the Cenozoic as far back as the Oligocene or Eocene. The fossil materials came from oil-well cores, and that from Kern County was taken from a depth of 10,450 feet. Pierce also described two insects, one of which is a katydid, from the Upper Miocene Valmonte diatomite of the Palos Verdes Hills.

## VERTEBRATE PALEONTOLOGY

### GENERAL STATEMENT

Growth of this division of the science on the Pacific Coast is probably best demonstrated by an increase in number of educational institutions in which vertebrate paleontology is cultivated as a research discipline. Where formerly the University of California represented the principal center, today important results of original studies not only emanate from that institution, but also from the University of California at Los Angeles, the Los Angeles County Museum, and the California Institute of Technology.

### FISHES

Especially noteworthy are the advances made in the knowledge of fossil fish. Between 1919 and 1927 were published a series of papers by David Starr Jordan (1920-1925; 1927), and Jordan and Gilbert (1919-1920), which dealt chiefly with Miocene fishes of Southern California. Jordan laid the foundations for future research in this subject, but almost 2 decades elapsed before these studies were resumed. The six papers by David (1943) describing Miocene fishes of Southern California not only furnish a clearer picture of the piscine faunas of this epoch than that previously available, but the information is utilized in an interpretation of ecologic and climatic conditions, and in other ways is helpful to the geologist. While her research is largely on Tertiary fishes, she has likewise described (David, 1941; 1944) a new species of *Leptolepis* from the Cretaceous of Nevada and a large petalodont shark from the Permian of the Grand Canyon, Arizona. Hesse (1936) described a new species of *Priscacara* from the Roslyn Eocene of central Washington. The fish is most nearly related to species of the same genus known from the Green River shales, Wyoming. In the realm of the late Paleozoic, attention should be directed to the interesting account by Wheeler (1939) of the peculiar elasmobranch, *Helicoprion*, and its stratigraphic significance in Nevada and California.

Of particular promise are the investigations on fossil fish scales by David. Earlier work by Cockerell (1919) and by Rumbley (1931) touched upon the subject, but its value as a research discipline and in applied paleontology is only now clearly comprehended as a result of David's studies.

### REPTILES

A second notable advance in vertebrate paleontology is the discovery of fossil reptiles (mosasaurs, plesiosaurs, and hadrosaurian dinosaurs) in the upper Cretaceous (Moreno formation) of the middle Coast Ranges, California. The occurrence of some of this material was discussed by Stock (1939), and splendid memoirs on the mosasaurs (Camp, 1942a) and on the plesiosaurs (Welles, 1943) are now available. A mounted skeleton of one of the plesiosaur genera (*Morenosaurus*) has been prepared at the California Institute of Technology. In the memoir by Welles some material of an elasmosaurid plesiosaur from the Benton Cretaceous of Colorado is described, and a revision is made of previously known North American elasmosaurs. Fragmentary remains of an ichthyosaur from the marine Cretaceous of Oregon furnished the subject for a brief report by J. C. Merriam and Gilmore (1928). Incomplete ichthyosaur rostra, preserved in chert cobbles of a Quaternary gravel bed, were described by Camp (1942b). These specimens possess special significance since their original deposition occurred apparently in the Franciscan formation. They throw added light, therefore, on the geologic age of an important group of rocks from which very little fossil material of any kind has been obtained. Camp (1936) also described from the Navajo sandstone (Lower Jurassic), Arizona, a small bipedal dinosaur, the type of a new family.

Loye Miller (1942a) identified the chelonian remains from the McKittrick asphalt as belonging to the desert tortoise, *Gopherus agassizii*, thus adding a reptilian species

to the long list of Pleistocene vertebrates known from the locality. Presence of the desert tortoise is further evidence that arid climatic conditions prevailed during the period of accumulation of the brea deposits.

### BIRDS

Most of the contributions in the special field of avian paleontology relate to Pleistocene birds and avifaunas, although important Tertiary finds have also been described. The Rancho La Brea collection of mounted fossil bird skeletons on exhibit at the Los Angeles County Museum represent a unique assemblage, having no equal in the world. It includes the brea stork, extinct turkey, Merriam's teratorn, condor, caracara, and other birds of prey.

Loye Miller (1922-1942b) and Hildegarde Howard (1927-1941) continue to publish their valuable studies of the Rancho La Brea avifauna. In recent years Howard and Alden H. Miller (1939) reported on the birds associated with human remains in Pit 10, Rancho La Brea, which assemblage belongs to a later stage in time than that found in the typical Pleistocene deposits. The fossil passerine birds from the latter were identified by Alden H. Miller (1929), and this author discussed the broader implications of the fauna with reference to biotic association, life zones, and climate (1937; 1940).

The Pleistocene avifauna from the McKittrick asphalt likewise received considerable attention by Loye Miller (1922; 1925a; 1929a; 1935). Important reviews of the bird life recorded at McKittrick, and in the Carpinteria asphalt, were made by Ida DeMay (1941a; 1941b). The passerines from the latter locality were reported upon by Alden H. Miller (1932). A new genus of pigmy goose, described by Ross (1935) from the McKittrick Pleistocene, has since been recognized in the Rancho La Brea avifauna (Howard, 1936). The bird assemblage from the Pleistocene of Fossil Lake, Oregon, has been reviewed by Howard (1946). This valuable contribution for the first time brings order to an important avifauna comprising species whose identification, made by Shufeldt, left the faunal list in a chaotic state. Splendid summary accounts of the fossil birds of California were published by Loye Miller (1923; 1925a) and by Miller and DeMay (1942).

Ranking next in importance to the studies on the brea avifaunas are the investigations by Loye Miller (1925b; 1929; 1935) on Miocene marine birds from Lompoc, Calabasas, and Palos Verdes Hills, California. The only other published record of Miocene birds from marine deposits (Temblor formation) is that by Wetmore (1930).

Small lots of fragmentary remains furnished the basis for identification of birds from the Barstow Miocene (Loye Miller, 1925), Esmeralda Pliocene (Burt, 1929), Ricardo Pliocene (Loye Miller, 1930b), Kern River Pliocene (Loye Miller, 1931), Etchegoin Pliocene (Wetmore, 1940), San Diego Pliocene (Loye Miller, 1937), Santa Barbara Pliocene deposits (Howard, 1932), as well as from the San Pedro Pleistocene (Loye Miller, 1930a; 1934). Present practice of describing new types of birds on isolated and fragmentary skeletal elements may give rise to difficulties when an attempt is made later to determine the relationships of fossil birds of one formation to those of another, unless the opportunity of finding associated parts of skeletons occurs more frequently than is now the case.

It is interesting to note in passing that the study of fossil birds, although generally limited in other regions by a scarcity of materials, has here attracted additional workers within the era under review. Only one of these is professionally known as an avian paleontologist. This group is responsible for the fact that in America the West has taken the lead in number of contributions to paleoornithology.

### MAMMALS

During the past 25 years or more researches on fossil mammals have undergone vigorous prosecution, and the program of investigation shows no sign of abating. Knowledge of Tertiary land mammals on the Pacific Coast has increased with penetration of the geologic record from the Upper or Middle Miocene to and including the Upper Eocene. The discovery of fossil mammals in the Tecuya beds (Stock, 1920; 1932), in the Sespe formation (Stock, 1930a; 1932b–1935a; 1935b; 1935e; 1938a), and in the Poway (Stock, 1937–1939a) brought to light assemblages having great significance in the evolutionary record and in establishing correlations between lower Tertiary horizons on the Pacific Coast and those in continental formations of the Great Basin, Rocky Mountain, and Great Plains provinces. New types of mammals, as for example the genus *Eohaplomys* (Stock, 1935b), assist in tracing back in time the phylogenetic history of particular groups, in this instance to an early stage in the evolution of the aplodont rodents. Another early Tertiary mammal occurrence was recently reported by Stirton (1944) from the Clarno formation, Oregon.

Other important studies of fossil mammals and mammalian faunas from areas in California where continental deposits are associated with or intercalated in marine formations are those by Gazin (1930) on the Cuyama fauna, Maxson (1930) on the Mint Canyon fauna, Matthew (1930) on a Pliocene mastodon in the Etchegoin formation, Russell and VanderHoof (1931; VanderHoof, 1933a) on Pliocene mammals from the Tehama formation, VanderHoof (1931) and Barbat and Weymouth (1931) on the occurrence of *Borophagus* in the marine Tertiary, Bode (1931; 1933–1935) on the mammals from the *Merychippus* zone of the north Coalinga district, Stock (1935c) on the deepest well record in North America of a Tertiary land mammal, Stirton (1939c) on Cenozoic mammals from the San Francisco bay region, Dougherty (1940) on a Miocene assemblage from Caliente Mountain, Jahns (1939; 1940) in his contributions to the stratigraphy and Miocene faunas of the easternmost Ventura basin, and Richey (1938; 1943) on assemblages from Black Hawk Ranch and from the Orinda formation. Mention should be made also of Drescher's studies (1941) of elements of the Chanac fauna from the Tejon Hills. These reports mark substantial additions to the knowledge of continental deposits and faunas intercalated in the dominantly marine Tertiary sequence of the Pacific Coast. They form, with work previously done, some of the foundation blocks on which broad correlations are made (J. E. Eaton, 1939; H. E. Wood, 2nd, *et al.*, 1941), thus intergrating the later geologic history of the West Coast with that of other parts of the American continent.

Appointment of Dr. W. D. Matthew to a professorship in paleontology at the University of California in 1927 gave new impetus to the development of a broad program of investigation at that institution. In part this was expressed by the exploratory activities of his associates in regions to the east of the Great Basin prov-

ince as well as in the West. The death of this eminent scholar in 1930 terminated a career that held great promise of further accomplishments in a region richly endowed with research opportunities. His interest in mammalian history and in problems of correlation has been continued by others, shown particularly by the paper by Teilhard and Stirton (1934) on a correlation of some Miocene and Pliocene mammalian assemblages of North America and Asia, and those by Stirton (1936; 1939b) on the succession of North American continental faunal units for the Pliocene and Miocene.

Although paleontologists continued to explore some of the well-known Tertiary formations of the Great Basin province, greater interest has been evinced in the discovery of new deposits and horizons. Continuation of the investigations at some of the older and well-known localities include a further study of the faunas from the John Day basin, of the Thousand Creek Pliocene fauna, northwestern Nevada, clarification of age of the Esmeralda fauna (Stirton, 1932), and the extensive exploration of the Barstow Miocene and Ricardo Pliocene by Frick (1926; 1937; *see also* Osborn, 1933). Several years earlier Frick (1921) had initiated work in California by the discovery of fossil mammal remains near Eden Springs, in San Timoteo Canyon, and in the Bautista badlands. The extent of the newer investigations in the Great Basin Province is shown by the following contributions; (1) fossil mammals from Fish Lake Valley, Nevada (Matthew, 1929; Stirton, 1929; Hall, 1929; 1930a, 1930b), (2) a Miocene fauna from near Skull Springs, Oregon, by Gazin (1932), (3) late Cenozoic rodents from southwestern Idaho by Wilson (1934a; *see also* Gazin, 1934), (4) a Miocene fauna from Sucker Creek, Oregon, by Scharf (1935), (5) late Cenozoic vertebrates from the Coso Mountains, California, by Wilson (1932) and by Schultz (1936), (6) mammal-bearing beds near Death Valley, California by Stock and Bode (1935), (7) Pliocene mammals from Smiths Valley, Nevada (Wilson, 1936a; Furlong, 1943), (8) Tertiary mammals from the Avawatz Mountains, California, by Henshaw (1939), and (9) a Tertiary mammalian fauna from the San Antonio Mountains, near Tonopah, Nevada, by Henshaw (1942). The Miocene studies in Oregon demonstrate the presence of a widespread fauna closely related in age to the Mascall of the John Day basin. This complex of mammalian species establishes more fully, than would be possible from the Mascall fauna alone, the age relationships of the latter. Late Tertiary vertebrates from the Sierran region of California were described by Merriam and Stock (1933), VanderHoof (1933b), and Stirton and Goeriz (1942).

Individual kinds of mammals have received special study. Thus Matthew (1931–1932) discussed the history of the Rhinocerotidae, Stirton (1935; 1940) the beavers and the Equidae, and Wilson (1937) the Pliocene rodents of western North America. Wilson (1940a; 1940b; 1940c) likewise described a number of new and interesting early Tertiary forms. Furlong (1941) discussed the relationship of the later Tertiary antelopes, while Frick (1937) published a large work on the horned ruminants of North America in which are found descriptions of a number of western forms. Colbert (1938) made a special study of western Pliocene peccaries. Hall discussed the fossil ring-tailed cats (Hall, 1927) and the Mustelidae (Hall, 1936), and more recently (1944) published an enlightening paper on Pliocene badgers.

Among Quaternary studies the brea faunas again take a prominent position. The

memoir on the edentates by Stock (1925) gave a detailed account of the ground sloth remains from Rancho La Brea. A similar monographic treatment of the Felidae from this locality by Merriam and Stock (1932) appeared 7 years later. Among the shorter contributions may be mentioned one on peccary remains (Merriam and Stock, 1921b), a paper discussiong the relationships and structure of the short-faced bears (Merriam and Stock, 1925), and a report on the shrews (Compton, 1937). Stock (1929) attempted to make a census of the Pleistocene mammals from Rancho La Brea, and later (Stock, 1930b) published a guide book to the collections at the Los Angeles County Museum. This publication was revised and reprinted 12 years later.

Meanwhile preliminary papers on the newly explored brea occurrences at McKittrick (Merriam and Stock, 1921a) and Carpinteria (Stock, 1927) had appeared, and descriptions of some of the mammals were published (Stock and Furlong, 1927; Stock, 1928). A complete account of the Carpinteria mammalian fauna was published by Wilson (1934b), and a similar report by Schultz (1938) on the much larger assemblage from McKittrick appeared 5 years later.

Although fossil elephant remains were known to occur on the Channel Islands, off the coast of Southern California, more than 65 years ago, interest in these forms was awakened as a result of paleontological explorations on the islands by the California Institute of Technology during the twenties (Stock and Furlong, 1928; Stock, 1935d; Wilson, 1936b).

Fascinating results have come from cave explorations and the uncovering of cave deposits. These studies have added significance because some of the assemblages belong to that latest stage in geologic time in which man makes his first appearance in North America (Stock, 1936; 1941). Moreover, remains of extinct mammals found in cavern sites in the arid Southwest are, on occasion, unusually well preserved as a result of desiccation. In the instance of the ground sloth, *Nothrotherium*, found in Gypsum Cave, Nevada (Stock, 1931), and in Rampart Cave, Arizona (Wilson, 1942), not only were its skeletal parts recovered, but pieces of the integument, hair, horny sheaths of the claws, and dung are, likewise, preserved. The scatological studies of some of this material (Laudermilk and Munz, 1934; 1938) yielded information of value in an interpretation of habits and habitat of the creatures to which they pertain. This unusual type of preservation may be expected when further Quaternary cavern accumulations are discovered in the Southwest, particularly in the Sonoran desert.

A substantial number of papers relating to Neogene Cetacea of the Pacific Coast have appeared. The early Tertiary toothed whales or Archaeoceti are singularly absent in the West, and this is all the more remarkable since marine Eocene formations are not lacking.

Knowledge of fossil whales on the West Coast increased considerably during the past 2 decades due in large measure to the splendid, detailed yet broad, studies by Remington Kellogg. Others have contributed as well, but Kellogg's world grasp of the subject and his thorough understanding of the natural history of the Cetacea make his judgments on the structural characteristics, evolution, and geographic distribution of fossil whales in this region authoritative and especially valuable.

Most of the fossil whales come from the Miocene. Thus, Kellogg has described a humpback from the Lompoc diatomite (1922a), a physeteroid cetacean from the Monterey formation (1925a), a long-beaked porpoise from the Vaqueros (Kellogg, 1932), a cetothere from the Modelo (1934), and, with E. L. Packard, a cetothere from the Astoria formation, Oregon (Packard and Kellogg, 1934). By far the largest assemblage of marine mammals known from any locality is that recorded by Kellogg (1931) from the Temblor Miocene at Shark-tooth Hill in Kern County. The Temblor fauna includes primitive whalebone whales (cetotheres), delphinoid porpoises, a squalodont or shark-toothed porpoise, a sperm whale (Kellogg, 1927a), two pinnipeds, and *Desmostylus*. An interesting feature of this study is the use made by Kellogg of the periotic in describing 7 new genera and 10 new species of fossil porpoises from this locality. Kellogg found that the ear bones are diagnostic and can be relied upon in identifying these animals. From the Temblor formation east of Bakersfield, California, Leslie E. Wilson (1935) described several new genera of porpoises. Associated with these is *Eurhinodelphis*, a long-beaked porpoise found in the Calvert Miocene of Maryland. A primitive cetothere skull was recorded also by Kellogg (1929) from near Saugus, California. Although said to have come from the Pliocene, the specimen may belong to the Miocene for its structural peculiarities suggest a stage in the evolution of these whales older than Pliocene. Porpoises of the later Cenozoic are, likewise, recorded by Allen (1924) from near San Francisco and by Gregory and Kellogg (1927) from San Diego.

Kellogg has appreciated the need for accurate geologic location of fossil whale specimens. The wide pelagic distribution of the Cetacea make the evolutionary stages in the history of the group of great value in establishing transoceanic correlations. It is, therefore, highly desirable to determine their stratigraphic position with regard to that of other fossils, particularly micro-organisms. As yet no occurrence on the Pacific Coast has yielded an abundance of material, the remains of an entire school of whales for example, of any particular type or species. This, consequently, has not permitted an analysis of the structural characteristics to determine the degree and extent of their variation. It appears possible that in organisms of such large size, somewhat different criteria will have to be employed in the recognition of species and genera from those now applied to smaller animals. In this connection it may be of some significance to note that on the Pacific Coast the same species of fossil whale has not been recorded from horizons of same or similar age that are widely separated geographically.

From the diatomite at Lompoc, Kellogg (1925b) described the sea cow, *Metaxytherium jordani*, and a second occurrence of the genus was reported more recently by VanderHoof (1941) from near Santa Cruz. The genus evidently was extensively distributed during the Miocene, for it is found in formations of this age in Florida and in Europe as well. A comprehensive report on the fossil sirenian, *Desmostylus*, was published by VanderHoof (1937). This genus was distributed along the northern margin of the Pacific basin from Japan to California. In the marine Tertiary of the Pacific Coast it had, however, a limited stratigraphic range, occurring only in the Briones and Temblor. An antecedent type, recognized as the distinct genus, *Cornwallius*, by Hay (1923), from the Sooke beds of Vancouver Island, British Columbia,

has since been recorded by VanderHoof (1942) from the east coast of Lower California.

Some additions were made to the known fossil record of the Pinnipedia, although the advance in knowledge is by no means so great as that of the Cetacea and compares rather with that of the Sirenia. Following his earlier studies (Kellogg, 1921; 1922b), Kellogg (1925b) described two new kinds of eared seals from the Lompoc Upper Miocene diatomite, noting that these represent a more modernized stock than the archaeic forms previously described from earlier stages of the Miocene in California and Oregon. In that year, also, he described the hind flipper of the Pliocene pinniped, *Pontolis* (Kellogg, 1925b). Two years later, Kellogg (1927b) described an otarid from the Santa Margarita formation. In the same paper were noted remains of sea lion and true seal from Pleistocene deposits of California. In his discussion (Kellogg, 1931) of the pelagic mammals from the Temblor formation of the Kern River region he gives a detailed account of the skeletal elements of *Allodesmus*, an extinct eared seal which he had previously described from this locality. Ten years elapsed before another paper dealt with a fossil pinniped from the Pacific Coast. Gretchen Lyon (1941) called attention to a sea lion found in the Miocene diatomite near Lomita, California.

The paleontological data gathered during the past years are available not only to the specialist, but to the lay reader as well. Thus, J. C. Merriam (1930) published a series of illuminating and instructive essays in which were emphasized the broader meaning and the reality of several noteworthy fossil occurrences. Popular accounts of a number of paleontological discoveries made in the West have been published from time to time by Stock. Apparently, no worker on the Pacific Coast has as yet felt a sufficiently strong urge to publish a textbook in paleontology. However, while none has appeared, one or two are projected. Nearest approach to a text was the discussion of the general principles of the history of life by Matthew (1928), based on a syllabus of lectures on paleontology given by J. C. Merriam and published many years ago by the University of California. No review of the progress in vertebrate paleontology is complete without due acknowledgment of the indispensable bibliographies in this subject by Camp and VanderHoof (1940), and by Camp, Taylor, and Welles (1942).

## PALEOBOTANY

With the exception of the description of a cycad from the Mariposa slates, Tuolumne County, by Wieland (1929), a discussion of the occurrence of a Pennsylvanian flora from central Oregon by Read and C. W. Merriam (1940), the comprehensive work of Daugherty (1941) on an Upper Triassic flora from Arizona, the papers on Permian plants of the Grand Canyon published by David White (1929) during the concluding years of his life, and one or two additional papers, there have been no further contributions to the literature on fossil plants of the Paleozoic and Mesozoic. Publications in paleobotany scored heavily, however, for the Cenozoic. The outstanding contributor in this field is R. W. Chaney, who initiated his work during the period 1919–1921. Since then he has made the University of California the center

for paleobotanical research in the West, and a number of individuals have contributed much in research in this region.

Starting with his description of the Eagle Creek flora, collected beneath the Columbia lavas in northern Oregon (Chaney, 1920), Chaney soon turned to the fossil plant assemblages that are found in the John Day and Crooked River basins of that State. Presence of several well-preserved floras and a readily established stratigraphic position for individual fossil assemblages made these areas ideal to work in. Chaney (1924; 1925a) reported on the Bridge Creek flora, on the Mascall Miocene flora (Chaney, 1925b), and on the paleobotany and stratigraphy of the Crooked River basin (Chaney, 1927). Meanwhile, Knowlton (1926) had published on a well-preserved flora from the Miocene Latah formation, occurring in Washington and Idaho. Three years later appeared a revision of this assemblage by Berry (1929).

The investigations by Chaney and his associates extended into other parts of the Northwest, and a number of important publications appeared. Thus, Chaney (1922) noted some characteristics of the Payette flora of Idaho, Chaney and Sanborn (1933) described the Eocene Goshen flora, MacGinitie (1933) the Trout Creek Miocene flora of southeastern Oregon, Oliver (1934) a Miocene flora from the Blue Mountains, Dorf (1936) a late Tertiary flora from southwestern Idaho, Sanborn (1937) the Comstock Upper Eocene flora from the west-central part of Oregon, and Chaney (1938a) the Deschutes flora. In addition, Mason (1927) included, in his survey of fossil records of some west American conifers, a number of plant types collected in this area.

Paleobotanists of the east and middle west manifested an interest in the fossil floras of the northwestern States, and particularly of Idaho, during the middle and late thirties. In contrast to the collections made by western students, the materials which furnish the basis for these studies have found a repository in the U. S. National Museum, the Carnegie Museum, and the University of Michigan. Berry (1934) described a large number of fossil plants from many localities in Idaho, and these were regarded as being related in age to the Latah Miocene. Additions to this flora were made by Brown (1937a; 1937b), who likewise discussed the fossil plants from older and from previously unrecorded localities in Washington and Oregon.

The Sucker Creek flora from southeastern Oregon and southwestern Idaho had received attention by Berry, Chaney, and later by Brown. Brooks (1935) on the basis of a large collection discussed this Miocene assemblage, pointing out its ecologic implications and age relationships. Arnold (1936; 1937) noted the occurrence of *Cedrela* in the Miocene of western America and published some observations on fossil plants from eastern and southeastern Oregon. Smith (1938a; 1939a) contributed further information concerning the Sucker Creek flora. This author (Smith, 1938b; 1939b) likewise described fossil plants from the Idaho formation near Weiser, southwestern Idaho, and called attention to a flora of eastern American aspect in Miocene beds exposed northeast of Boise.

Knowledge of Tertiary plant assemblages from California and Nevada was also increased. Thus, Chaney (1921) described a fossil flora from the Puente formation, Dorf (1930) gave a full account of the Pliocene floras of California, Chaney (1932) noted the occurrence and age of fossil plants in the auriferous gravels of the Sierra

Nevada, Axelrod (1934; 1937) described the Pliocene flora from the Mt. Eden beds, Riverside County, Potbury (1935) the La Porte flora of Plumas County, MacGinitie (1937) the flora from the Weaverville beds, Trinity County, and a middle Eocene flora from the central Sierra Nevada (MacGinitie, 1941), Condit (1938) the San Pablo flora of west-central California, Axelrod (1939) a Miocene flora from the western border of the Mohave desert, LaMotte (1936) the upper Cedarville fossil plant assemblage of northwestern Nevada and adjacent California, and more recently Axelrod (1940a; 1940b) the Mint Canyon flora, California, and the Pliocene Esmeralda flora, Nevada. In a volume recently published, and edited by Chaney (1944), are a number of articles describing Pliocene floras from California and Oregon by Chaney, Condit, and by Axelrod. This contribution also reviews the history of Pliocene floral studies in western North America and discusses the terminology applied to vegetational units of the Tertiary as well as the taxonomic principles involved in a study of Pliocene floras. It given an excellent summary statement of the relationships of these Pliocene and Mio-Pliocene assemblages, their geologic, topographic, climatic, and ecologic significance, and their stratigraphic and geographic distribution. The concluding comments relate to the topographic and climatic conditions which have influenced the composition and distribution of these floras. The fossil materials forming the basis of the many studies indicated above are, for the most part, leaf impressions often beautifully preserved in rock. Relatively little work has been done on petrified wood. Webber (1933) described the woods from the Ricardo beds. Most intensive study of this type of material has been made in recent years by George F. Beck (1935).

Discussion of the broader implications of these paleobotanical investigations have been published by Chaney (1936a; 1938b). Since the student of fossil plants of the Cenozoic notes comparatively little phylogenetic change among the conifers and angiosperms in their evolution from the Cretaceous to the present, individual stages in this evolution cannot be so readily recorded on the basis of structural characteristics as in the case of more complex organisms like mammals. Hence, the paleobotanist must devise other methods by which the geologic age of fossil floras can be established from the plant materials available to him. A method, largely developed by Chaney (1936b), is the use of geographic space relationships of floras as a guide to the age of fossil plant assemblages in western North America. Concordant with this concept is the view that in this region the climatic trend for the Tertiary shows a progressive lessening of rainfall from the Eocene to the Pliocene inclusive. In the practical application of these views, Chaney and his associates make a definite departure from the procedures employed by earlier paleobotanists. The studies of Tertiary and Pleistocene plant assemblages have been enormously productive of data that are valuable in paleoecology (Chaney, 1938b).

Because Pleistocene floras are often extremely well preserved, they have attracted particularly the attention of students. Plant assemblages of this age were described by Frost (1927), Mason (1927) from Rancho La Brea, by Chaney and Mason (1930) from Santa Cruz Island, by Potbury (1932) from San Bruno, San Mateo County, California, by Chaney and Mason (1933) from the Carpinteria asphalt, and by Mason (1934) from the Tomales formation.

As in the instance of vertebrate paleontology, the number of students contributing to research in paleobotany has shown an appreciable increase during the past 2 decades or more. Where formerly Lesquereux and Knowlton were the principal contributors to the knowledge of Cenozoic floras of the west, there are more than a dozen students. In contrast to vertebrate paleontology, paleobotany is much more centralized on the Pacific Coast, for there is but one research laboratory with large comparative collections located in this region.

## PALEOPATHOLOGY

This is, as yet, a little-cultivated field of research which may be expected to furnish information of significance to paleontology and medicine. So far, the contributions have been principally those of R. L. Moodie, and these relate almost exclusively to the evidences of disease among the Pleistocene animals of Rancho La Brea. Thus, Moodie (1928–1930) in a series of papers called attention to the vertebral lesions in the sabre-tooth which resemble *spondylitis deformans* and the so-called *myositis ossificans progressiva*, to the occurrence of luxations among Pleistocene mammals, to a suggestion of rickets, and to the phenomenon of sacralization in *Smilodon*. His studies in paleodontology (Moodie, 1928–1930) included such subjects as the evidence of pyorrhea, dead teeth, and gingival infections in lower jaws of the dire wolf, impacted teeth and abscess in the sabre-tooth, facial asymmetry in the sabre-tooth with loss of the canine tooth, and apical closure of root canals in teeth of adult Pleistocene carnivores. These papers are in large measure descriptive, and the diagnoses are tentatively expressed. However, they emphasized the fact that the prevailing cause in many cases of Pleistocene pathology was trauma. Since the death of Doctor Moodie in 1934, work in the field of paleopathology has ceased.

## SUMMARY STATEMENT

A comparison of the period under review with that prior to 1917 leads to a definite conclusion that in net activity and in achievement the researches in paleontology during the former surpass those of the earlier period. Not only were the older research disciplines cultivated to excellent advantage, but many new investigations came into existence and have undergone vigorous development. The most striking instance of this is micropaleontology which shows a prodigious growth.

Much of the paleontological research on the Pacific Coast concerned itself with faunal and stratigraphic problems in which geologic correlation plays an important role. The link between paleontology and geology is probably stronger than that between this science and biology. Much descriptive work is still being done, but this is not so much an expression of primary interest in classification as it is a means to an end. Acquisition of more information regarding genera and species as well as description of new types have not given rise to new views or concepts in the theory or philosophy of evolution. Phylogenetic studies, especially those of vertebrates, were conducted, and these clarified the relationships within certain groups. In such investigations greatest progress has been made in the instance of the mammals, less for the invertebrates, and least for micro-organisms and fossil plants. Comparative

morphological studies, like those of Kellogg (1928) on marine mammals and of Camp and Smith (1942) on the phylogeny and functions of the digital ligaments of the horse, are of infrequent occurrence. Paleoecology received some attention by students, but this discipline would welcome more devotees.

As Weaver (1944) recently pointed out, the development of micropaleontology on the Pacific Coast has given rise to two schools with reference to the classification of Cenozoic formations. In future, therefore, further progress should be made to reconcile these views in order that a unified system might prevail and permit a more detailed correlation with sections elsewhere in North America and in western Europe than is now the case. In this regard, vertebrate paleontology and particularly the recognition of evolutionary stages in the geologic history of marine mammals ought to find a prominent place. It also seems desirable to treat the microfaunal records of the remaining epochs of the Cenozoic as comprehensively as Kleinpell has done for the Miocene.

The trend toward greater use of biometric methods in paleontology, strongly advocated in some quarters, has not progressed far, as yet, on the Pacific Coast. Such methods were applied in the study of the avian genus, *Parapavo*, by Howard and Frost (1927). More recently, Schenck and Keen (1936; 1937) developed methods for analyzing marine molluscan provinces on the West Coast and for making comparisons of molluscan faunules. Biometry as applied to measurement data derived from large collections like those from the Pleistocene brea deposits would yield valuable results.

Unquestionably, the progress of paleontological investigation quickened not only because some of its results possessed great economic value but, likewise, because adequate financial support was available for pure research. Such support was furnished by munificent individuals, petroleum companies, and by institutions or societies interested in research like The Geological Society of America, the Carnegie Institution of Washington, the American Philosphical Society, the Wellcome Foundation of London, and others. Whether these favorable circumstances will continue to prevail in the period which lies ahead remains to be seen. There can be no question however, as to the fundamental worth of paleontological research and teaching in the field of education. Moreover, the number and value of the research problems that still await solution have not diminished. So vigorous has been the present program of investigation that the impetus behind it will undoubtedly project these research activities well into the future.

An indication of the stage of maturity reached by paleontology on the Pacific Coast are the explorations conducted by western workers in areas farther afield and in foreign lands. This is not so much an expression of diminishing interest in regions near at hand, but rather the result of a broadening horizon in paleontology.

Some of the last geographical frontiers have been reached in the westward shift of exploratory field work across the United States. These frontiers, however, are far from becoming exhausted in the production of new facts. Fortunately, the region, whence have come the materials for research, is featured by a dynamic geologic history in which the episodes in the development and movement of life are often well defined. The complexity of this historical sequence offers a challenge that no inquiring

student of paleontology can ignore. For those who are specifically interested in the paleontology of the Pacific littoral, the eastern margin of the basin with its evidences of former marine portals extends invitingly to the north and to the south. The world significance of the basin in the Pacific era which lies ahead bodes well not only for continued interest in paleontology, but also for an accelerated rate of accomplishment.

Nor is this all that the paleontologist and geologist may look forward to. Today distance is no longer a handicap in the conduct of exploratory work. Just as the automobile made possible a wider sphere of activity and a fuller as well as a more rapid acquisition of materials and information than were possible in the days of the horse and wagon, so today does the airplane make distant regions more accessible and fosters thereby a truly world-wide acquaintance with fossil records. We should grasp the opportunities which the newer technology and a change in international relationship afford us. The facilities for paleontological field studies in Africa, Mongolia, the Near East, Siberia, or South America are today probably even more adequate than those which were available in the exploration of our western badlands during the nineteenth century.

With these opportunities, however, come also added responsibilities. We should, for example, give full cognizance to the national rights of those countries in which our paleontological collecting is done. Lest we come ultimately to face in foreign lands the establishment of bans or statutory restrictions on the collecting of fossils, such as are even now in existence in certain of our States, we should not only preach the gospel of co-operation, but practice it in deed as well.

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# GEOMORPHOLOGY OF THE MIDDLE KERN RIVER BASIN, SOUTHERN SIERRA NEVADA, CALIFORNIA

BY ROBERT W. WEBB

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## ABSTRACT

Evidence from study and mapping of erosional levels, from reconstruction of dissected drainage divides, and from geological relations of a volcanic series proves that the Kern River has always followed a southerly course in its cutting in the Kern River Basin, refuting the deductions of Lawson (1904) that the Kern flowed eastward from the upper Kern Basin across Toowa Valley. Structural control of the Kern River by the Kern Canyon fault is shown to have been effected at the beginning of the older of two cycles; principal evidence is found in the plotted erosional surfaces preserved throughout the basin. The Great Western Divide is established as the primary division of drainage in the southern Sierra prior to the development of the Sierra Nevada fault. A hitherto unrecognized period of canyon cutting is recorded by channels cut in the Chagoopa level, now buried by flows, but visible in the walls of Little Kern gorge. Volcanism, in two stages, and periodic movement on the Sierra Nevada fault stagnated and diverted drainage in both tributary and master streams.


## INTRODUCTION

### GENERAL STATEMENT

The geologic record in the Kern River Basin of the southern Sierra Nevada of California (Fig. 1) consists of two parts: (1) from late Paleozoic or early Mesozoic through the latest Jurassic (Hinds, 1934), expressed in the basement complex of metamorphic and igneous rocks; and (2) from the final petrologic episode of the complex to the present, consisting of a fragmentary geomorphologic record, which contrasts with the intricate but readily discernible pre-Jurassic history. The clearer parts of the record are latest Tertiary and Quaternary. No direct evidence of pre-Pliocene history is available; the only diagnostic post-Jurassic deposit is a volcanic series partially preserved in several small, isolated areas.

This paper presents new evidence for events in the evolution of the Kern Basin and supplements and revises some of Lawson's (1904; 1906) interpretations. Some major problems are: (1) the anomalous position of the Kern River in Sierran[1] drainage—a large south-flowing river on a mountain mass of prevailing east-west slope and drainage; (2) the magnitude and influence of Kern Canyon fault in the basin history; (3) relations of volcanism to geomorphic history; and (4) drainage history of the river system. The area is covered principally by the Kernville and Olancha topographic quadrangles. These maps, and the Mt. Whitney quadrangle, should be consulted when reading this paper.

### GEOGRAPHY

*General.*—The Sierra Nevada extend northwest-southeast for 400 miles in eastern California. Kern River, draining about 2200 square miles, is the master stream of the southern quarter of the range. It is the only large north-south-trending stream in the Sierra Nevada. Kern River rises on the west slopes of Mt. Whitney and flows south 60 miles to be joined by its principal tributary, the South Fork, which flows in

[1] The word "Sierran" is used in this paper as the adjective of "Sierra", without significance as a stage in the erosional history of the Sierra Nevada as employed by Hershey (1902).

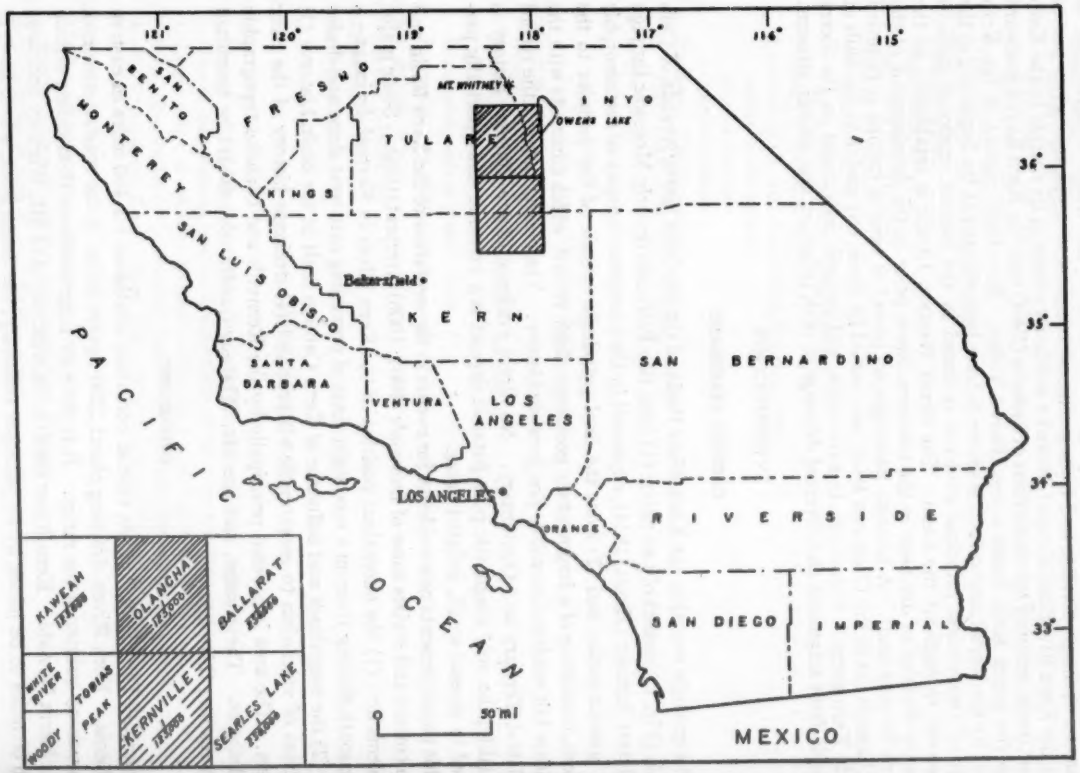


FIGURE 1.—*Index map of the Kern Basin, Southern Sierra Nevada of California*

from the east at Isabella (Fig. 2).[2] Below Isabella, the Kern turns sharply southwest and flows nearly 60 miles to the San Joaquin Valley near Bakersfield, California. This paper discusses the 40-mile segment between Isabella and Golden Trout Creek, known as the middle Kern. This section is covered in part by Lawson's (1904; 1906) contributions.

*Terminology.*—The terms Kern River Basin, Kern River Valley, Kern River Canyon, and Kern River Valley system have all been applied to the drainage area of the Kern River. In this paper, usage will be:

(1) Kern Basin: Entire drainage area of Kern River and its tributaries, from Kernville northward.
(2) Ancestral Kern Basin: Entire drainage area of the Kern River and its tributaries, in all erosion cycles preceding the present.
(3) Ancestral Kern Valley: Valley occupied by Kern River in the cycles preceding the present.
(4) Kern Canyon: Present canyon of Kern River.

## FIELD PROGRAM

Studies began in the fall of 1933; in the summers of 1935 and 1936 the northern Kernville quadrangle was mapped. The quadrangle map was completed in 1938 (Miller and Webb, 1940). Several reconnaissance trips into the Olancha quadrangle were followed in 1939 by systematic work there. Two summer months of 1940, and one in 1941, completed the mapping. A summary of work to 1940 has been published (Webb, 1941).

## ACKNOWLEDGMENTS

Residents of the area co-operated in many respects, particularly Mr. Charles E. Andress, of Weldon, California, and Mr. and Mrs. Cliff Willoughby of Little Lake, California. Mr. E. R. Shellenbarger, Lone Pine, California, Forest Supervisor in the Mt. Whitney area, was especially helpful. During summers Robert P. Bryson, Ross Cabeen, Thomas Donlon, Myles A. Colligan, Garnet W. Oliver, Parke D. Snavely, and Norman W. Schultz assisted in field work. I wish to emphasize my indebtedness to Mr. Bryson, now of the U. S. Geological Survey, for his continued interest in this project. He aided in many problems. Stimulating conversations and assistance in preparation of the manuscript has been given by many professional associates, among them W. J. Miller, Ian Campbell, James Gilluly, Cordell Durrell, W. C. Putnam, George H. Anderson, and J. Hoover Mackin. Mr. François E. Matthes and Dr. A. O. Woodford read the manuscript and offered suggestions for which the writer is especially grateful. Mr. Matthes freely shared the benefits of his wide field experience and the results of yet unpublished work on this and adjacent areas. To all who gave so freely of their energy, I express my deepest gratitude; to many others whose names do not appear here, I owe an expression of great appreciation. Field expenses were covered partially by grants from the Committee on Research, University of California, Los Angeles.

[2] Principal place names referred to in text are located on Figure 2.

FIGURE 1.—*Index map of the Kern Basin, Southern Sierra Nevada of California*

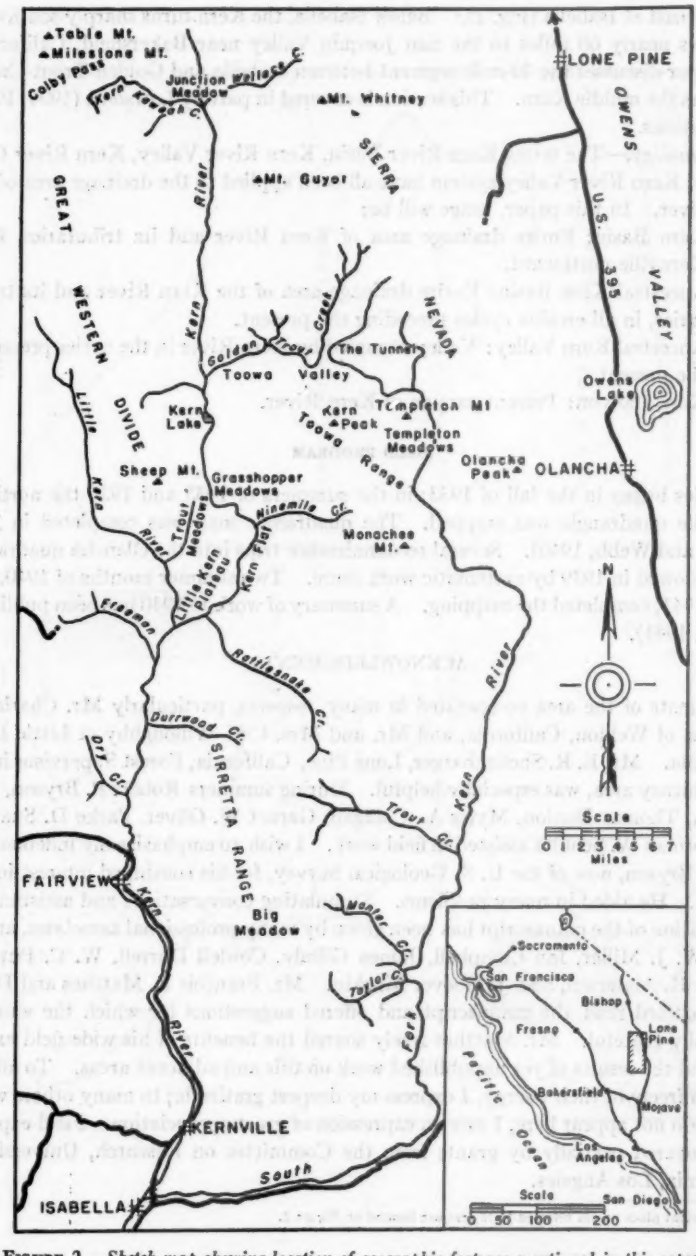


FIGURE 2.—*Sketch map showing location of geographic features mentioned in this report*

## SKETCH OF THE REGIONAL GEOLOGY

### PETROLOGY

*Metasedimentary rocks.*—The Kernville series—phyllites, quartzites, and marbles with small amounts of metamorphosed pyroclastics—form roof pendants and xenoliths, in areas of 3 to 40 square miles. The phyllite is commonly greenish gray to grayish blue, highly foliated, varying on intrusive contacts to mica schist, interbedded with thin light-gray to bluish-gray quartzites. Massive quartzite also occurs in thick zones, often constituting the pendants described commonly as septa (Mayo, 1935; 1937; Webb, 1938) because of their narrowness (an eighth of a mile) and elongation (6 miles). Marbles are highly crystalline to massive, white to bluish gray, and invariably fetid. Lenses and beds are commonly 50 to 300 feet thick. These roof remnants strike N.30°–40°W. and dip usually more than 65°. Durrell (1940) discussed the metamorphism of rocks deemed in part at least their equivalents. Miller (1931) named the series the Kernville because of widespread occurrences near Kernville in Kern Canyon. No fossils have been found, and the age is therefore unknown. Lithologic similarity—no real criterion—suggests correlation with the Calaveras (Permo-Carboniferous) formation of the central Sierra Nevada (Miller, 1931; Miller and Webb, 1940), but the series may be equivalent to the Mariposa (Jurassic) formation (Miller, 1931; Miller and Webb, 1940), or Triassic (Knopf and Thelan, 1905; Knopf, 1918) or Devonian (Mayo, 1931).

*Plutonic rocks.*—Three intrusive units are common: (1) gabbro, followed by and intimately associated with (2) hornblende-quartz diorite, and (3) quartz monzonite, with many facies.

The gabbro, areally the most restricted, is medium- to fine-grained, with occasional porphyritic facies. The chief constituents are, by volumetric per cent: plagioclase ($An_{70-80}$), 80; hornblende, 18; biotite, pyrite, and other accessories, 2.

The quartz diorite is closely associated with the gabbro and often grades into it. The former is medium- to fine-grained, composed of plagioclase ($An_{40}$), 68; quartz, 12; orthoclase or microcline, 5; hornblende, 10; biotite, 3; and accessory apatite, sphene, and magnetite or ilmenite. Typical quartz diorite ranges from gabbro to occasional granodioritic facies.

The quartz monzonite, ranging commonly to granodiorite, is medium- to coarse-grained, with extensive porphyritic facies. Average volume percentages are: quartz, 30; orthoclase or microcline, 30; plagioclase ($An_{30-40}$), 30; biotite, hornblende, apatite, sphene, and magnetite range from 0–10 per cent.

The ages of the intrusives are not known, but the quartz monzonite is considered equivalent to the widespread, late Jurassic granitic intrusions of the Sierra (Hinds, 1934).

*Volcanic sequences.*—Flows, largely olivine basalt and agglomerate, lie on some upland surfaces of the range. These are 10–300 feet thick and especially extensive along Ancestral Kern Valley (Pl. 2, fig. 1). A younger (Lawson, 1904) sequence occurs, chiefly as cinder cones, along the high east-west Toowa (Lawson, 1904) valley, where four basaltic cinder and agglomerate cones, often breached, rise 200–600

feet above the valley floor. These eruptions have blocked drainage and are therefore probably very recent. Monachee and Templeton mountains, prominent peaks in the eastern Olancha quadrangle, are volcanic domes (Knopf, 1918).

*Alluvial deposits.*—Lacustrine and fluviatile sediments occur locally along streams and on upland surfaces. These are of small areal extent, with no regional importance.

### STRUCTURE

*Kern Canyon fault.*[3]—The only prominent structural feature within the southern Sierra is the Kern Canyon fault (Pl. 7), which trends north-south approximately half way between the eastern and western margins of the Sierra Nevada block. The fault is known to extend from Kernville northward about 40 miles to the mouth of Golden Trout Creek (Webb, 1936). North of here positive evidence of faulting is absent, although the trend of the Ancestral Kern Valley and Kern Canyon suggests structural control by a fault. Suggestive evidence is found as far north as Junction Meadows, where complexly jointed and slickensided bedrock occurs on the projection of the fault trace. A linear belt of pink granite (Lawson, 1904, p. 337) is seen high in the west wall of the Kern Canyon (Pl. 1, fig. 2). This pink granite forms by alteration along a major shear plane which is parallel to the canyon. This shear may be in the roots of the Kern Canyon fault zone. South of Kernville weak physiographic evidence suggests continuation of the fault. Geological studies are still in progress along the supposed southern continuation.

The Kern Canyon fault is a well-defined, mappable structural feature, known from physiographic, structural, and petrologic evidence. It is very old, produced probably during the development of the Nevadian Mountains, and only its roots are now visible. The direction and amount of movement on the fault are not known.

*Other faults.*—The faults bounding the Sierra on the east (Sierra Nevada fault) and on the west (a distributive fault system) have been described (Baker, 1912; Buwalda, 1915; 1920; Knopf, 1918; Hake, 1928; Miller, 1931). The writer made only brief reconnaissance of these faults. Within the southern Sierra proper, faults are infrequent; no other major ones have been mapped.

## BASIN FEATURES

### GENERAL CONSIDERATIONS

The geomorphic evolution of the Sierra Nevada has long been recognized as complex (Le Conte, 1889). Lawson (1904; 1906) first described the erosional surfaces within the southern part, especially along Kern Canyon, and the events which produced them. His suggestions were accepted until Matthes (1937) proposed revised definitions of the erosional surfaces. A detailed discussion of Matthes' ideas will be contained in a paper to be published on Sequoia National Park (F. E. Matthes, personal communication).

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[3] Not to be confused with the Kern River fault, which crosses the mouth of the Kern Canyon at the point where it enters the San Joaquin Valley. This fault has been described by Blackwelder (1927).

### NOMENCLATURE

*Lawson's subdivisions.*—Lawson (1904) recognized three major evolutionary episodes of the so-called High Country of the upper Kern Basin and classed surfaces cut during these episodes as zones. In the High Mountain zone were placed the highest Sierran peaks in the vicinity of Mt. Whitney, called the Summit Upland division of the High Mountain zone. A rolling platform below the highest peaks at elevations of about 11,000 feet was designated the Sub-summit Plateau, in the High Mountain zone. Some 2000 feet below the Sub-Summit Plateau, a system of high-level valleys are designated the High Valley zone, and in the Kern drainage proper the Chagoopa Plateau. This upland (Chagoopa Plateau) valley extends for many miles along the upper and middle Kern and is the most prominent topographic surface of the Kern Basin (Pl. 1, figs. 1, 2). The present cycle of stream erosion, characterized by a canyon stage, Lawson called the Canyon zone. It included the Kern Canyon proper. These designations are useful in describing similar features of the middle Kern, but Lawson applied them in the upper segment only.

*Matthes' subdivisions.*—Matthes (1937) modified Lawson's subdivisions. Lawson's Sub-summit Plateau was renamed the Boreal Plateau, and its extent and significance redefined. The designations Summit Upland, Chagoopa Plateau, and Kern River Canyon are retained, and Matthes' nomenclature is adopted here.

### SUMMIT UPLAND

The Summit Upland is best preserved on the peaks of Muir Crest—named by Matthes (1937, p. 6) for the range which includes Mt. Whitney and adjacent peaks on the eastern edge of the Sierra Nevada—and on the Great Western Divide west of Muir Crest. Flat-topped summits of peaks mostly over 13,500 feet high are placed in this division. The characteristics are described briefly by Lawson (1904) and more completely by Matthes (1937).

Lawson (1904, p. 307–308) wrote:

"The Summit Upland—This . . . has been characterized as consisting essentially of high peaks and crests. This, however, does not sufficiently describe the geomorphic character of these mountains, and some of their more striking features must be noted particularly. Several of the culminating portions of the summit divide are either flat topped, or have slopes which are so gently inclined as to be in sharp contrast to the more precipitous slopes which abound in the region. The best illustrations of such flat, or gently sloping, summits is that afforded by the summit range [Muir Crest] from Sheep Mountain to Cirque Peak. The summit of Mt. Whitney itself is nearly flat for perhaps half a mile square, with a very gentle slope to the west. This flat slope is surrounded on nearly all sides by precipices which are, for the most part, the walls of glacial cirques. Sheep Mountain, five miles south of Mt. Whitney, shows the same kind of a flat topped summit. . . . Similar characters obtain along the summit divide as far as Cirque Peak, and portions of the flatter summits even slope easterly, at a slight angle, to the brink of the precipices on that side. . . ."

Matthes (1937, p. 8–9) wrote:

". . . The Great Western Divide and its long north-northwestward and south-southeastward trending spurs, which must have originated in much the same way as the Muir Crest, bear several peaks with flat or gently sloping tabular summits. Most noteworthy is Table Mountain (13,636), between Milestone Mountain and the Colby Pass. . . . And on the Kern Ridge nearby are two more unnamed mountains with gently sloping summit platforms, 13,560 and 13,206 feet high, respectively. These tabular summits . . . clearly represent a group of ancient hills. . . .

"Farther north . . . still other tabular peaks dominate the skyline. Notable examples are

Mount Darwin, which has two detached summit platforms, 13,841 and 13,701 feet in altitude, respectively. . . . To those who have first hand acquaintance with these crests it is readily evident that their tabular summits, which decline steadily northward with the entire body of the range, represent isolated remnants of a once continuous landscape of moderate relief, an ancient lowland now raised to great height on the present range."

In the middle Kern Basin, few surfaces correlate with the Summit Upland, since most of the region is lower in elevation than the Muir Crest, which descends southward and dies away. However, on the Sierran front, Olancha Peak (12,135) has summit remnants which from profile appear to belong in the Summit Upland; Kern Peak (11,493), with considerable summit area, is similarly correlated.

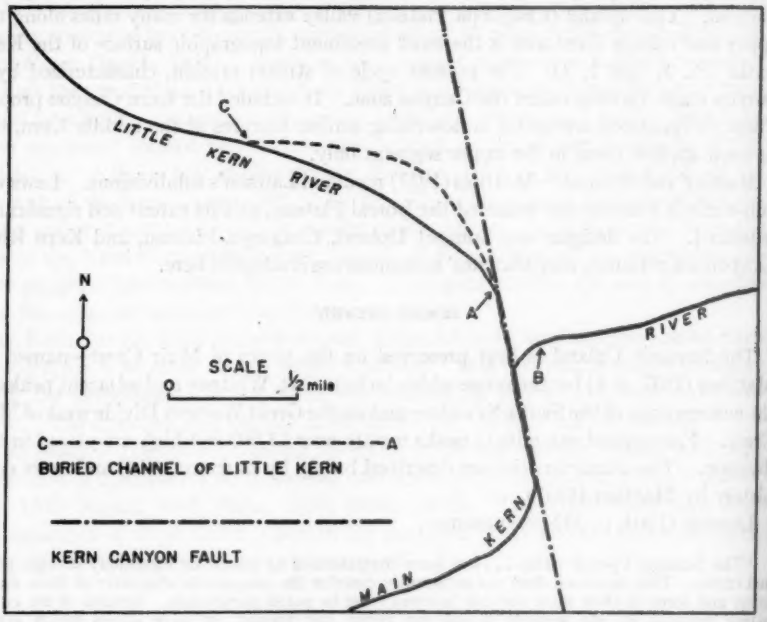



FIGURE 3.—*Explanation of relations pictured in Figures 1 and 2 of Plate 3*

### BOREAL PLATEAU

The Boreal Plateau, 1500–2000 feet below the Summit Upland, is the extensively preserved surface in the southern part of the range (Pl. 1, fig. 3). In nonglaciated areas, the plateau is covered with deep regolith and crossed by broad open valleys inherited from a previous cycle. Anastomosing streams flow across these valleys. Some trenching has begun, but generally rejuvenation has not extended to the high-level valleys, which are still drained by staggering, overloaded, low-gradient streams. Matthes (1937, p. 10) defined the surface in glaciated parts as follows:

"To the west of Cirque Peak, and about 1500 feet below the level of its rounded summit, is an undulating plateau that stretches unbroken for a distance of seven miles toward the Kern Canyon. The principal valley on that plateau, broad and level, goes by the name of Siberian Outpost. For

FIGURE 1. GENERAL VIEW OF MIDDLE KERN BASIN

Looking north from Durrwood Creek along Kern Canyon fault-line valley. Saddle in middle distance cut along fault. Little Kern Plateau of flat-lying volcanics in center of photo. Great Western Divide and Sierran Summits in background. Kern River flows in gorge indicated by arrows.

FIGURE 2. GENERAL VIEW DOWN KERN CANYON

Looking south from Junction Meadow. Possible continuation of Kern Canyon fault may be evidenced by notch in west wall of canyon, in which shear zone of "pink granite" is found. Chagoopa Plateau and other remnants of the ancient floor of the Kern on east and west.

FIGURE 3. GENERAL VIEW SOUTH FROM TAYLOR CREEK

Looking across even skyline of the southern Sierra, showing nature of upland surface, considered equivalent of Boreal Plateau. Average elevation 6000 feet. Mountain block shown is Kiavah Mountain.

GENERAL GEOMORPHIC FEATURES OF KERN BASIN

FIGURE 1. LITTLE KERN PLATEAU

Looking north up Little Kern River near junction with Main Kern (B), showing Little Kern Volcanic Plateau. Contact (– – –) between flows and granite basement is marked, (A) buried prevolcanic channel of the Little Kern River; (C) is position of headward part of buried channel of Figure 2.

FIGURE 2. GORGE OF THE LITTLE KERN

Looking east and south down Little Kern River across Little Kern Volcanic Plateau. (C) Buried prevolcanic channel of Little Kern River. (A) relative position of lower end of channel. *Compare* Figure 1, lettered identically for relative positions.

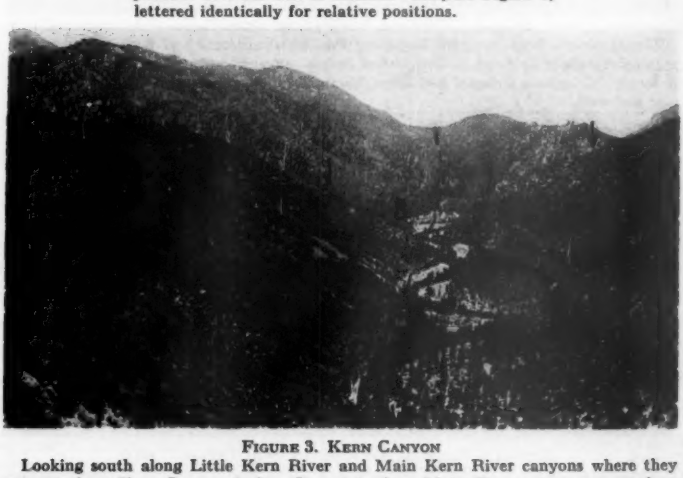


FIGURE 3. KERN CANYON

Looking south along Little Kern River and Main Kern River canyons where they are cut along Kern Canyon fault. (B) point where Main Kern enters; arrows show path of Main Canyon southward. Line indicates trace of fault.

the summit tract, which is of far greater extent than the valley . . . the name Boreal Plateau has recently been proposed. This plateau unquestionably represents a large remnant of an erosion surface of moderate relief that was formed throughout the upper Kern Basin during a prolonged period of erosion following a second great uplift. Other remnants of this ancient erosion surface are Guyot Flat . . . [and] . . . the Bighorn Plateau. . . ."

### CHAGOOPA PLATEAU

The Chagoopa Plateau, an upland area in the northern Kern Basin, is a distinct geomorphic feature with widespread equivalents in the basin (Pl. 2, fig. 1).

Lawson (1904, p. 315) wrote:

"The Chagoopa Plateau is, perhaps, the most remarkable feature of the basin of the Upper Kern. It is the ancient floor of the basin before it was trenched by the cañon of the Kern. That trenching, and all the long history that it involves, has left the ancient valley floor singularly intact. Its ancient characters, when it was still functional as a valley floor, are wonderfully preserved and fresh . . . it spreads out as a broad plain on the . . . [west] . . . side of Kern Cañon, extending from the brink of the cañon to the base of the precipitous eastern slope of the high mountains of the Great Western Divide. Its abutment on these mountains is a fairly sharp line; but there are transitional slopes, and the plain extends within the salient spurs of the high range. This edge of the plateau, skirting the base of the high mountains of the Western Divide, converges southward upon Kern Cañon in the vicinity of the mouth of Coyote Creek, and beyond that point the plateau is not traceable except, possibly, in certain doubtful terrace-like shoulders on the western side of Kern Cañon. . . .
(p. 316)—"To the east of Kern Cañon the Chagoopa Plateau has the same character and the same general altitude along the brink of the canyon as on the west side, but it is not so wide. . . ."

Matthes (1937), p. 11) wrote:

"About 1500 feet below the general level of the Boreal Plateau . . . lie the broad, gently sloping rockbenches that flank the Kern Canyon proper. Representative of these is the Chagoopa Plateau, which rises from an elevation of 8600 feet at the canyon rim to about 10,500 feet at the base of the mountains. Those benches are clearly remnants of a former floor of the Kern Basin that was developed to great breadth during an erosion cycle following a third uplift. . . ."

In the salient extending northward from the confluence of the Kern and Little Kern rivers lies the Little Kern Plateau. This nonglaciated platform has considerable summit area and is considered the southern extension of Chagoopa Plateau along Kern River (Pl. 1, fig. 1). In places lava veneers its surface and preserves many original features. The platform is trenched to depths of 100 feet by at least two stream channels filled with lava and visible in the walls of the Little Kern gorge (Pl. 2, figs. 1, 2). One channel is approximately parallel to the present-day Little Kern and is thought to have been cut by it. The other lies along the buried segment of the Kern Canyon fault and was cut at the same time by the Little Kern and one of its tributaries (Fig. 3; Pl. 2, fig. 3). The platform is covered elsewhere by a deep regolith now being dissected. Occasional stream cobbles found on this surface are too irregularly distributed to trace channels from them. Similar surfaces equivalent to the Chagoopa Plateau are found elsewhere in the general region.

### CORRELATION OF EROSIONAL SURFACES

The surface of greatest extent in the area is considered equivalent to the Boreal Plateau. The Chagoopa Level is preserved mainly in the Ancestral Kern Basin, along the Ancestral Kern Valley and Little Kern River. The profiles (Pl. 3) suggest the importance of the Great Western Divide as an ancient and probably original division of drainage in the Nevadian Mountains. Evidences considered in correlation

are: (1) capping of surfaces by equivalent deposits; (2) a similar stage of dissection in the erosion cycle; (3) similar elevations in present topography, and (4) similar sequence of surfaces from highest crests downward.

### KERN CANYON

*General description.*—Kern Canyon is divided into three segments: (1) a headward, north-south segment, deeply glaciated, 20 miles long from head to Golden Trout Creek; (2) the middle Kern, mostly nonglaciated, deeply incised, 40 miles long from Golden Trout Creek to Isabella; and (3) the lower Kern, 60 miles long, flowing southwest, to the San Joaquin Valley, in a deep rock-bound gorge being actively degraded (Pl. 5).

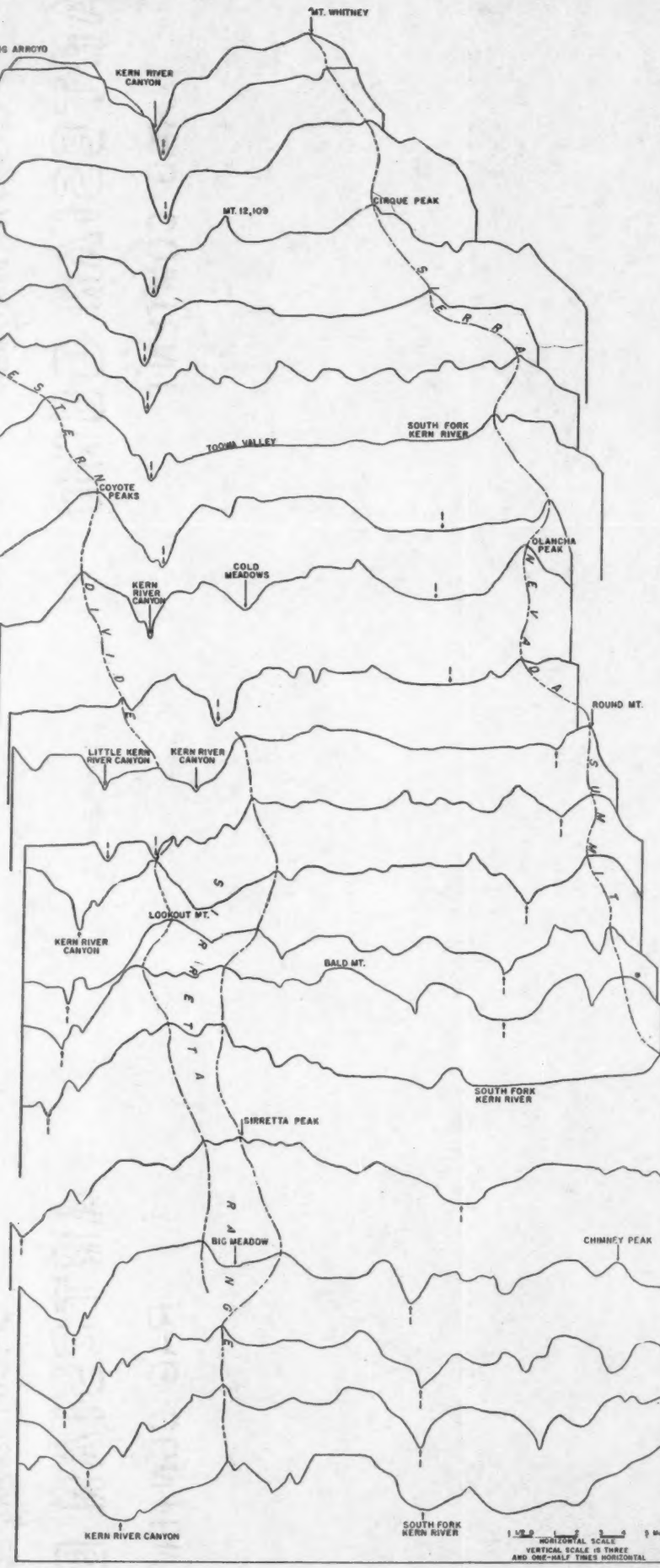
*Glaciated northern segment.*—Kern Canyon originates at Junction Meadows nearly due west of Mt. Whitney where Wallace and Kern-Kaweah Creeks join Kern River. In the Pleistocene glaciers scoured these canyons, coalesced at Junction Meadows, and pushed down the Kern to widen and deepen the Kern stream-cut canyon. Structural control by the Kern Canyon fault made the canyon straight, and rapid rejuvenation of the Sierran block made it deep. Glaciers moved down the canyon at least to the mouth of Golden Trout Creek. Matthes has discovered positive evidence of vigorous glaciation at least as far as 6 miles south of the junction with Golden Trout Creek. The U-shape of the canyon, and morainal deposits show glaciation. Matthes has studied the glacial history but has not yet published the results.

*Middle canyon segment.*—From Golden Trout Creek southward, Kern Canyon parallels the Kern Canyon fault. The canyon's direct southern course, however, swings abruptly eastward 6 miles south of Golden Trout Creek. Several variations in trend occur before the stream resumes an irregular but southerly course.

The central segment is the most rugged and sinuous. Deep-cut tortuous canyons, always rock-bound and often so narrow that the entire canyon width is occupied by stream, alternate with graded reaches. For 6 miles along the canyon south of Golden Trout Creek peculiar anomalous buttress-forming hills hug the west wall. They were called kernbuts by Lawson (1904, p. 331–332); between Golden Trout Creek and Grasshopper Meadows (Pl. 4, fig. 1) there are four sets of them.

Below Grasshopper Meadows, the river, continuing in a deep gorge, swings abruptly eastward, leaving the pronounced linear course cut along the Kern Canyon fault for the preceding 36 miles; it returns again to the fault 15 miles downstream. South of Grasshopper Meadows local alluviated flats caused by temporary base levels alternate with gorge topography. Local base levels are not found south of the junction of the Kern and Little Kern rivers; here the Kern swings west away from the Kern Canyon fault and flows 35 miles farther in gorge topography. North of Isabella for 10 miles the Kern is alluviated because of a local temporary base level at Isabella. Here the Kern River is forced westward from its valley by alluviation of the South Fork which there joins the Kern River.

*Lower canyon course.*—South of Isabella the river plunges into a rock-bound gorge of gentle gradient which steepens southward. For 50 miles the Kern is deeply entrenched, until it emerges upon the southern San Joaquin Valley floor. The longitudinal profile of the Kern River is shown (Pl. 5).

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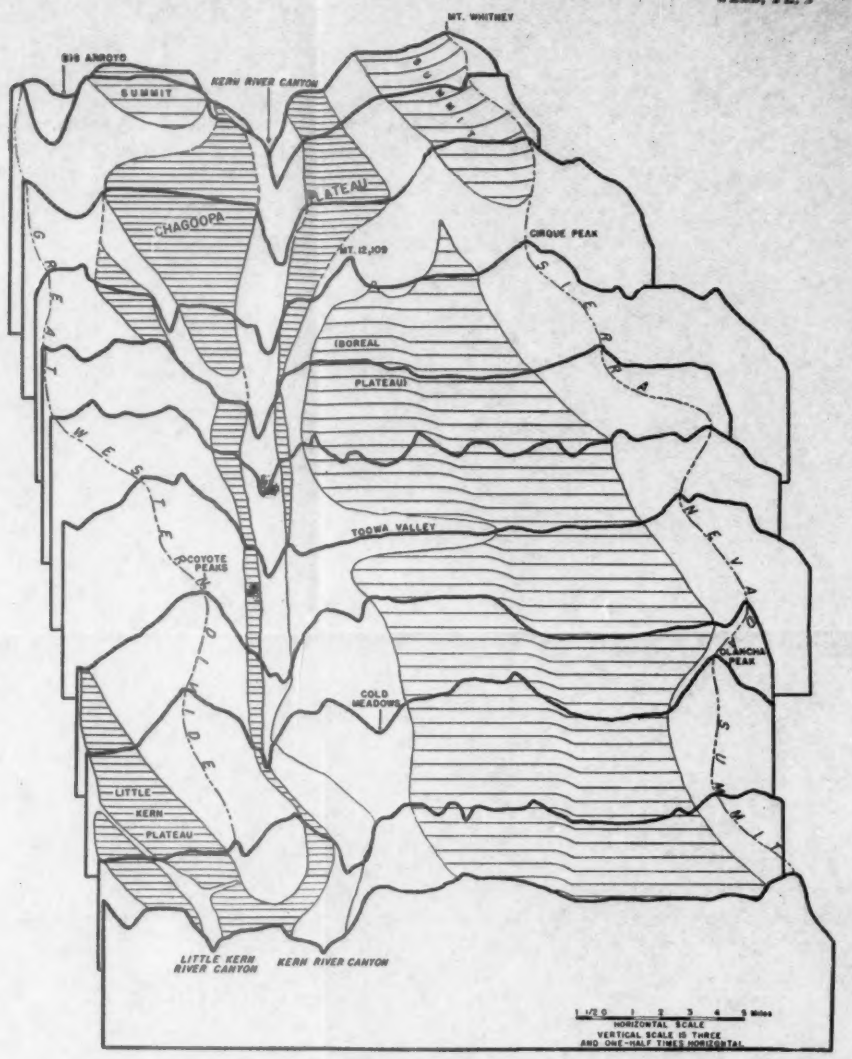


B

TRANSVERSE PROFILES OF KERN BASIN
A, PROJECTIONS; B, INTERPRETATIONS
Drawn to scale from Kernville, Olancha, and Mount Whitney quadrangles

### KERN CANYON DEFILE

Kern Canyon defile is a linear valley carved along the Kern Canyon fault from the junction of the Kern and Little Kern rivers south nearly to Kernville (Pl. 4, fig. 2). The fault is marked by a series of small valleys and intervening divides within and on the east side of Ancestral Kern Valley. Streams developed a prominent fault-line valley and rectilinear drainage patterns. The present river channel transgresses this fault-line valley. South of the Little Kern the fault-line valley lies east of the river, whereas north of it the valley is west of and parallel to the river. The fault-line valley, within the Ancestral Kern Valley, and subparallel to Kern Canyon, gives a dual character to the topography, with a high-level (fault-line) valley along the fault and a lower-level gorge along the river. This differential results from subsequent streams working headward along the fault from master tributaries of Kern River.

North of the Little Kern the fault is buried for more than a mile by lava flows, but it reappears northward in Trout Meadows.

### TROUT MEADOWS DEFILE

From Trout Meadows, a prominent fault-line defile extends northward for 6 miles (Pl. 4, fig. 3). Seldom over an eighth of a mile wide, and from 300 to 600 feet deep, this defile is found along the projected extension of the Kern Canyon fault. Along the defile landslides and fan accumulations from its east and west walls produced local temporary base levels in which playas have formed. Trout Meadows defile is an anomalous topographic feature which merges northward with Kern Canyon at Grasshopper Meadows.

### GREAT WESTERN DIVIDE

The Great Western Divide, the most prominent intramontane ridge of the southern Sierra, lies west of the Upper Kern Basin, extends southeastward, transgressing drainage trends, and thus continuing east of the lower Kern Basin. The intersection of ridge and river is near the Little Kern Plateau where the divide is lowest. Here the divide extends southeastward and is known locally as the Siretta Range (Pl. 3). The Great Western Divide has a maximum elevation of more than 13,000 feet in the north, decreasing to 6400 feet at the gap occupied by the Little Kern Plateau; it rises again southward to 9000 feet in the Siretta Range, descends, and merges with adjacent uplands near Big Meadow in the southern part of Kern Basin. That the Great Western Divide and Kern River intersect approximately where the Kern leaves the line of the Kern Canyon fault is significant in interpreting the cause of deviation.

### SOUTH FORK OF THE KERN

The South Fork has a most anomalous course. Through 50 of its 70 miles, it flows in valleys far too large to have been cut by it with its present volume. The stream apparently inherited pre-existing valleys and integrated them by subsequent erosion. It staggers except in segments between valleys where it plunges rapidly through gorges, only to meander across the next graded reach (Pl. 5). The descent from Templeton Meadows to the junction with the main Kern is 4500 feet in 60 miles. The

Olancha and Kernville topographic maps give an adequate picture. The headward segment of the stream has been captured several times. The stream flows across remnants of surfaces which possess equivalents on the Sierran summits to the north.

## VOLCANISM

### LITTLE KERN VOLCANIC FIELD

*General statement.*—Volcanic sequences in the middle Kern Basin have long been known (Lawson, 1904), but no systematic study of character, distribution, source, and relations had been made. Since the volcanicity is intimately interwoven with the physiographic history, a study of the volcanic rocks was undertaken.

*Description of sequences.*—The volcanic rocks are dominantly olivine basalt flows. Megascopically the rock types are identical—massive, black, with small olivine phenocrysts and occasional lathes of labradorite. Xenoliths of granitic basement are often included but are far less common than in the Kernville area to the south (Webb, 1941). Glassy facies are rare, but the groundmass of the normal basalt is usually hypohyaline. Microphenocrysts of olivine and labradorite are abundant.

Many flows contain vesicles amygdaloidal with natrolite and sometimes calcite. These volcanic rocks are proved flows by (1) vesicular facies on upper surfaces with massive nonvesicular bases, (2) crude columnar joints, dying out downward, but normal to the upper (and vesicular) surface, and (3) slight weathering of upper portions of each flow.

The number of flows vary from place to place, since the magma spread laterally along a main drainage line; thus the younger flows progressively overlap the older. The flows spread into embayments on the old (Chagoopa) land surface, the younger flows had thus the greatest original distribution. In palisades along parts of the Kern and Little Kern canyons, at least four distinct flows are visible, 40–50 feet thick, each with crude columnar jointing. In some areas more flows occur, but very thin weathered zones between flows often make separation difficult where compositions are identical. Since pre-volcanic topography was irregular, occasional thick valley fills complicate tracing of individual flows. Seldom is the total thickness more than 400 feet.

*Distribution.*—Plate 7 shows the distribution of the volcanic rocks. Few residuals occur south of Freeman Creek. Similar composition, location in palisades adjacent to Kern River, and position of flow remnants on the Chagoopa benchland relate the residuals to a single episode of volcanism. The minimum southerly advance down the Kern barely reached the Kernville quadrangle where the most southerly mesa cap of basalt occurs. This mesa is at least 20 miles below the basalt source, thus suggesting marked fluidity in the erupted material. South of Freeman Creek the residuals are largely from late flows since they are massive in contrast to the earlier vesicular flows of Little Kern Plateau.

*Source.*—The flow material originated in the headward drainage of Little Kern River. Mapping is completed to the boundary of Kaweah quadrangle; reconnaissance has not located the exact source.

FIGURE 1. NEAR LITTLE KERN LAKE

Looking north from Grasshopper Meadows toward Kernbut of Figure 1. Kernbuts prominent in background. Dotted area marks large landslide which ponds Little Kern Lake.

FIGURE 2. KERN CANYON DEFILE

Chagoopa terrace in foreground along Kern River Canyon with prominent ridge in middle distance behind which lies fault-line defile cut along Kern Canyon fault. Arrows mark defile. Note canyons cut across ridge, streams of which are attempting to keep pace in down-cutting with the master Kern. Looking south from Dry Creek.

FIGURE 3. TROUT MEADOWS DEFILE

Alluviated defile along Kern Canyon fault, looking north toward head. Note terraces resulting from dissection by headward erosion.

### TOOWA VOLCANIC FIELD

*General statement.*—The number, sequence, and character of the volcanic cones and flows of Toowa Valley (Lawson, 1904) have been examined. Lawson (1904, p. 319) named Toowa Valley from the Toowa Range; it embraces the high east-west valley drained to the west by Golden Trout Creek (known also as Volcano Creek or Little Whitney Creek) and to the east by South Fork of Kern River. The volcanism largely developed flow and cone sequences in Golden Trout drainage where a volcanic field extends today half a mile to a mile wide and 4–7 miles long.

Toowa Valley, broad and open, averages 8600 feet in elevation, slightly less to the west, with volcanic cones rising 400–600 feet above the flow veneer. Volcanic activity is so recent that soils and vegetation on cones are sparse. The latest volcanism caused drainage stagnation; two prominent volcanic cones lie along the axis of the valley—South Fork Cone where Golden Trout Creek enters Toowa Valley, and Groundhog, 2½ miles to the west. Two other volcanic centers lie in the valley, one at the head of Little Whitney Meadow, and one at the Tunnel, north of South Fork Cone.

*Character of the rocks.*—The volcanic rocks are olivine basalts and basaltic agglomerates. Several effusive episodes are recognizable, but mappable units are more commonly based on textural and structural differences and on field relations rather than on compositional differences. Massive black olivine basalt, basalt scoria, banded red basalt, clinkery basaltic aa, cinders, and agglomerates are some of the types.

*Stages of volcanism.*—Several stages of eruption are recorded. Cinder cones, and lava flows extending 6 miles west of their vents down Golden Trout Creek, are characteristic. One highly vesicular flow emanated from the base of South Fork Cone and flowed west down Golden Trout Creek, where it is overlapped by younger flows from the Groundhog center. Tongues of lava from Groundhog, source of the most extensive eruptions, went as far west as Kern River. These flows filled a canyon previously cut in Toowa Valley. The transverse profile of this canyon is visible in the present east wall of Kern Canyon at the mouth of Golden Trout Creek. A more detailed account of Toowa volcanism is now being prepared.

### OTHER VOLCANIC SEQUENCES

Isolated mesas of volcanics occur on some summit levels in Kernville quadrangle. These, usually petrologically similar to those of Little Kern Plateau, have been described (Webb, 1941). Probably they are time equivalents of those of Little Kern Plateau, although evidence is lacking. Knopf (1918, p. 73) briefly described Templeton Mountain at the east end of Toowa Valley and Monachee Mountain south of Templeton, both volcanic centers.

## DRAINAGE DEVELOPMENT OF THE KERN BASIN

### GENERAL STATEMENT

Earliest studies (Drake, 1897, p. 570; Lawson, 1904; 1906) of Kern Basin recognized structural control as probable for a stream which maintains southern drainage

in a region of westward slope. No studies of the beginning of such control or of present-day influence of it have been published. In this paper the Kern Canyon fault is advanced as the responsible structural agent, and its present and past effects are analyzed.

## LAWSON'S RIFT HYPOTHESIS

Lawson (1904; 1906) postulated a Kern Canyon rift and discussed its influence on Kern drainage. His hypothesis supposes a rift controlling the trend of Kern Canyon. Crustal rifting (Lawson, p. 342) involved differential slippage within a fault zone or narrow orographic block in which movement occurred without dislocation of adjacent surfaces. Concurrent erosion cleansed the rift and made the graben character of the valley less apparent. Renewed movement accentuated the graben features.

Lawson (1906, p. 409) extended his graben hypothesis to explain features as far south as Kernville:

> "... For the Upper Kern the conclusion was reached that the canyon had been controlled as to its course by a rift line antedating the canyon and that at a later period faulting had occurred along this rift with partial engulfment of a narrow orographic block or wedge. The Middle Kern lies along the southward projection of this rift line through the Trout Meadows defile, and there seems little room for doubt but that its course, like that of the Upper Kern, was determined primarily by a great north-south crustal rift. At a later period when the canyon had been deeply incised the region was deformed and dislocation was effected along the general line of the rift."

Lawson (1906, p. 403) suggests that the east face of the Greenhorn Mountains, bounding the Middle Kern on the west, should show a fault. No evidence of such faulting was found during careful field study. The influence of faulting is closely confined to the defile against the east wall of the Kern Canyon for the 30 miles from the Little Kern junction to Kernville.

## ANALYSIS OF RIFT HYPOTHESIS

Several aspects of the crustal-rifting hypothesis are open to serious doubt: (1) It is difficult to imagine a graben as narrow as the Kern Canyon in which repeated movement produced no visible effect on adjacent erosion surfaces accordant on either side. (2) The graben, if of sufficient magnitude to control the river course for 30 miles from Junction to Grasshopper Meadows, should exert similar control on the rest of the canyon, whereas the river leaves the graben line and flows eastward about 4 miles in a canyon dissected as much as the topography along the graben. Discordance of graben and stream channel has developed in two places along the 60-mile segment under structural control. (3) The graben is buried beneath lava flows on the Little Kern Plateau. Study of the pre-lava surface shows that the trace of the graben was planed by erosion, prior to burial. Thus, if graben features were originally present, they existed in an earlier cycle. (4) No displacement of the volcanics has occurred; the latest faulting must have been, therefore, prevolcanic. It is concluded that the present-day canyon resulted from causes other than graben.

## PREFERRED HYPOTHESIS

*General statement.*—Any interpretation of Kern River history depends upon the Kern Canyon fault as the control of the drainage system, but the magnitude of its

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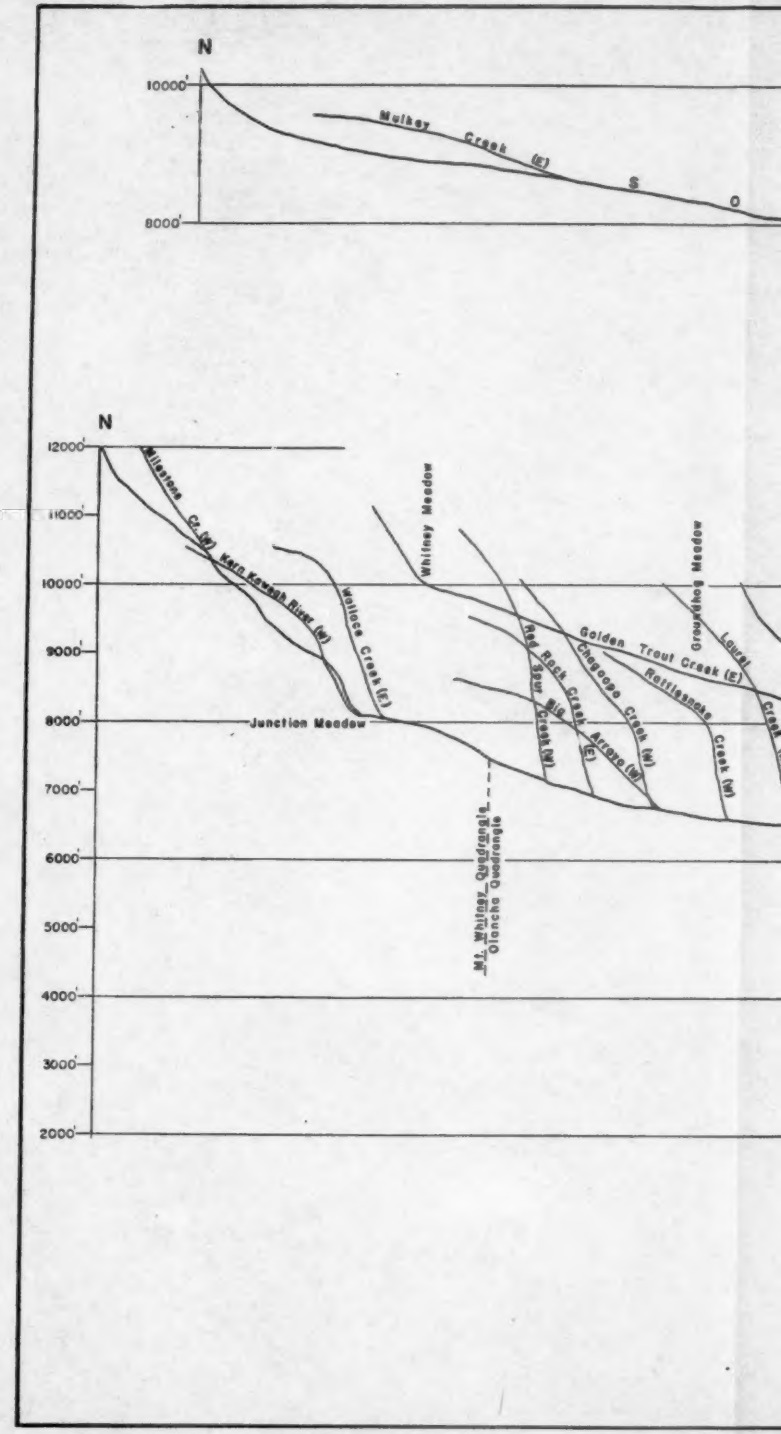
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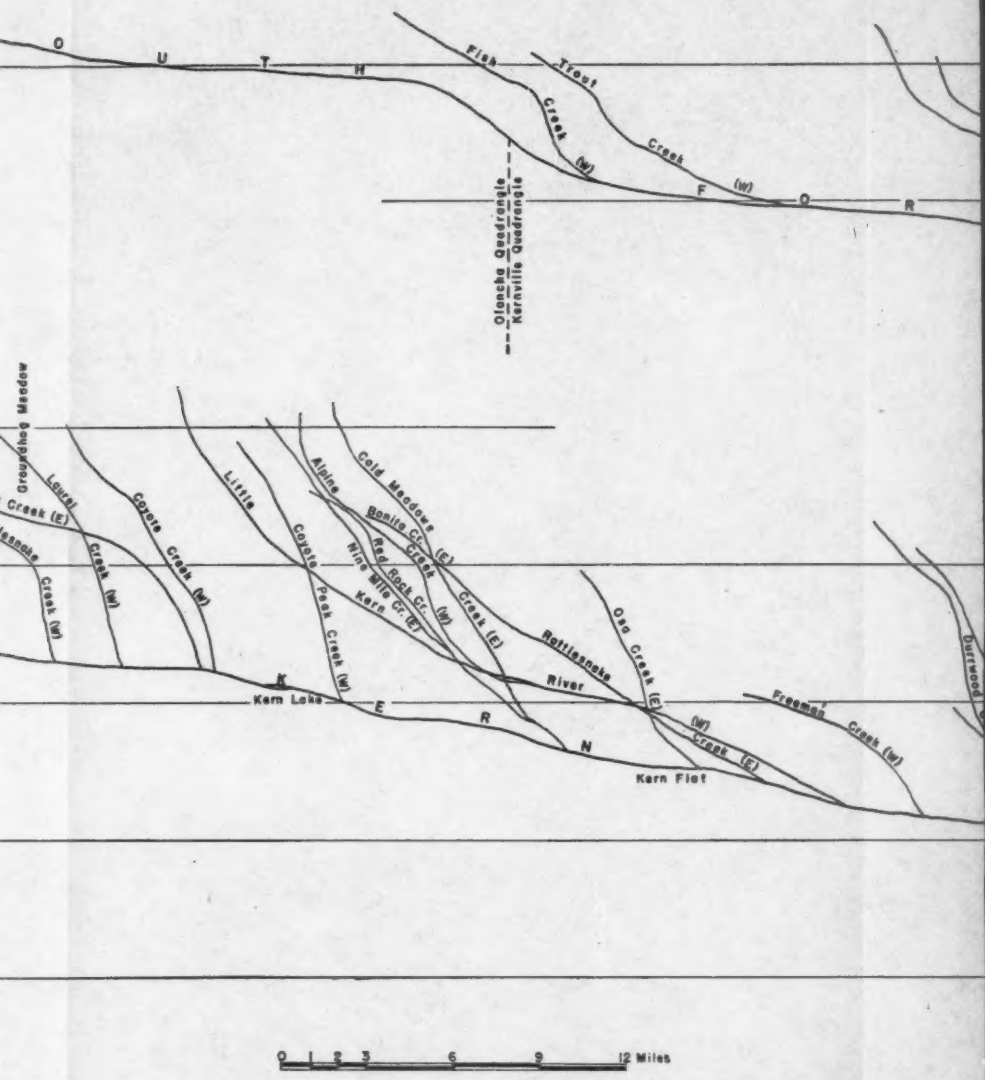
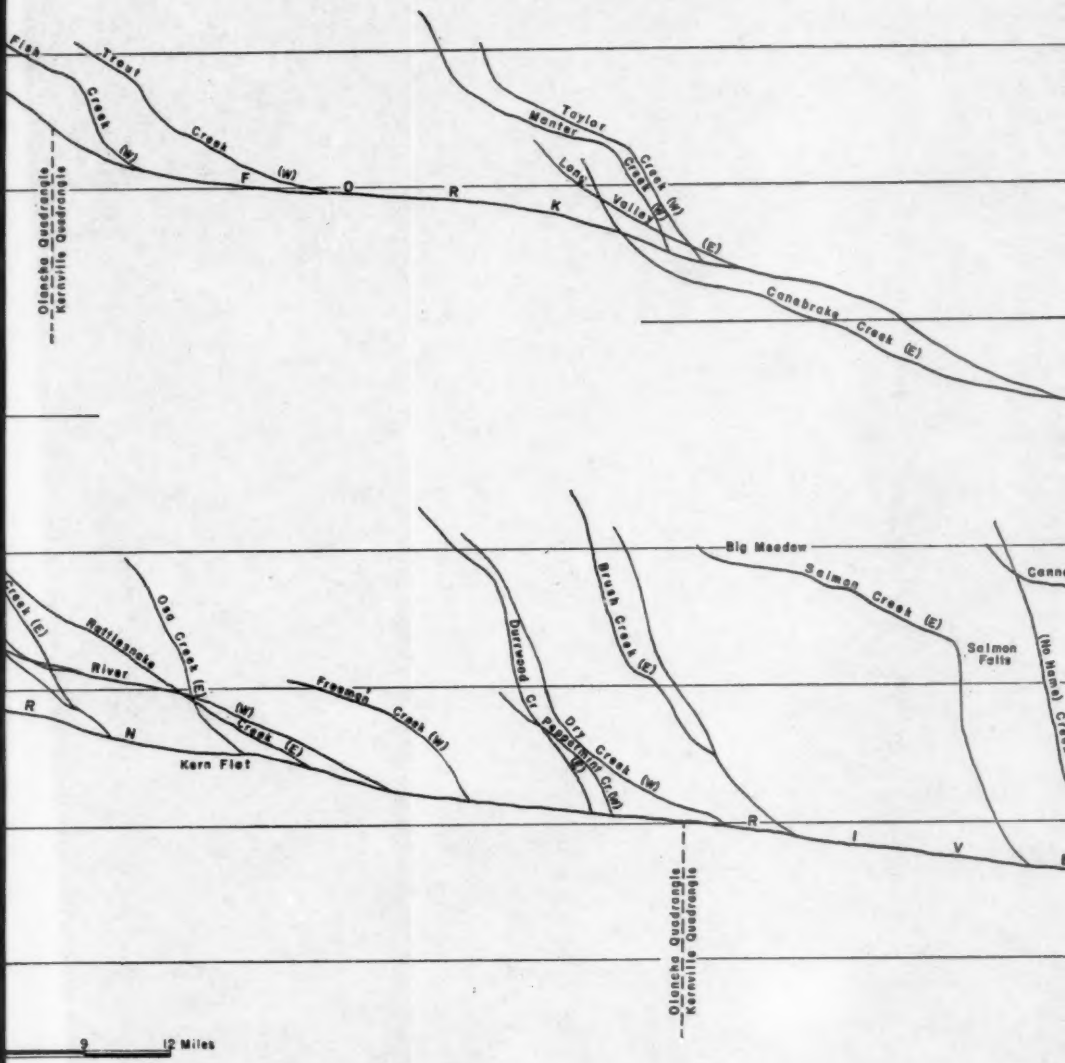
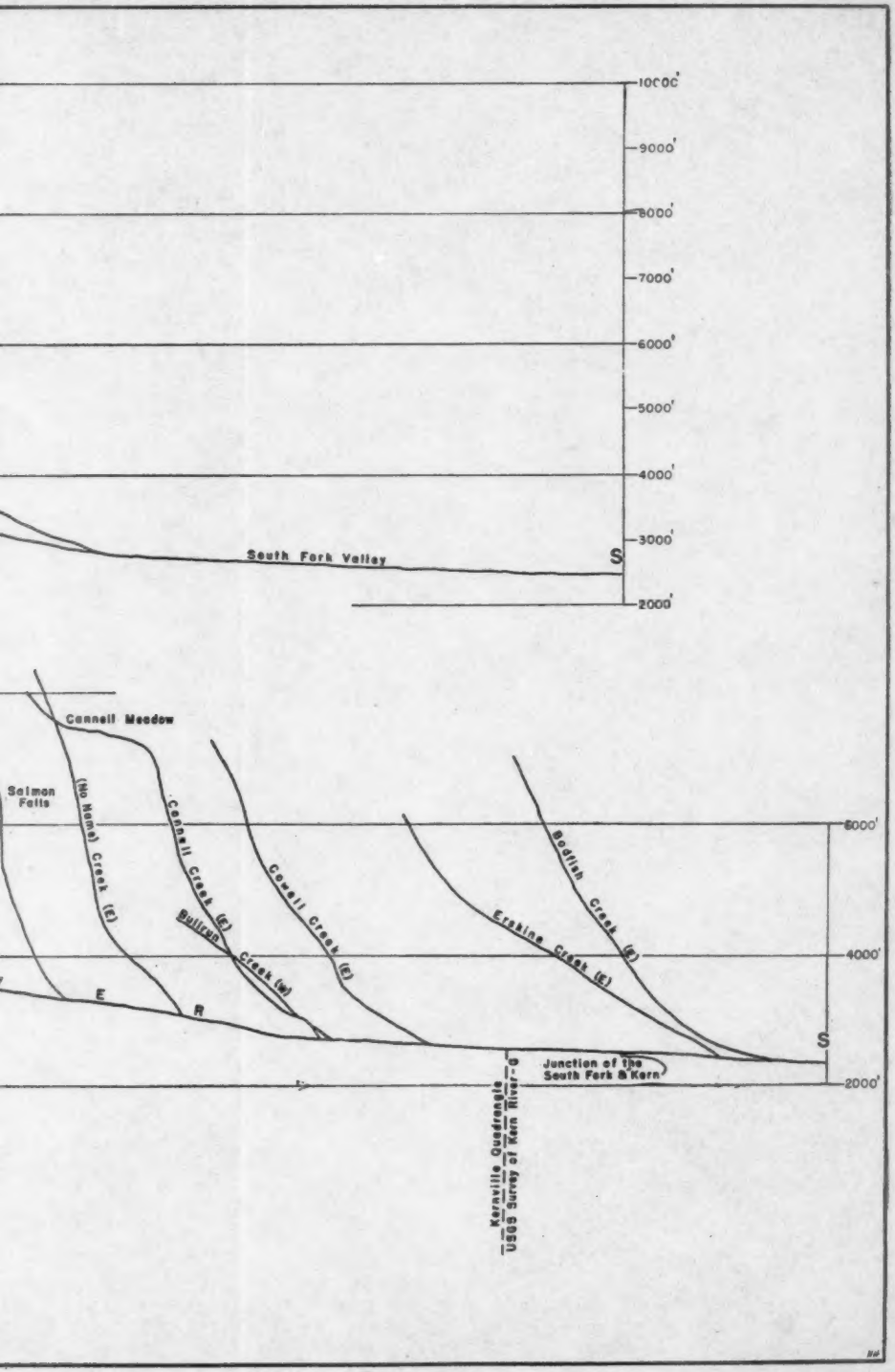
Kern Kaweah River (W)
Wallace Creek (E)
Whitney Meadow
Junction Meadow
Golden Trout Creek (E)
Rattlesnake Creek (W)
Chagoopa Creek (W)
Arroyo (W)
Mt. Whitney Quadrangle
Olancha Quadrangle




LONGITUDINAL PROFILES OF THE KERN RIVER AN
After M. Swinney




DINAL PROFILES OF THE KERN RIVER AND ITS IMPORTANT TRIBUTARIES
After M. Swinney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South Fork Valley
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Cannell Meadow
Salmon Falls
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Cannell Creek (E)
Bullrun Creek (W)
Cannell Creek (E)
Erskine Creek (E)
Bodfish Creek (E)
6000'
4000'
2000'
S
E
R
Junction of the South Fork & Kern
Kernville Quadrangle
USGS Survey of Kern River-0

influence is questionable. In the present interpretation all features are effected by erosion after faulting.

*Drainage of the Kern in past cycles.*—Transverse profiles (Pl. 3) of the Kern Basin show prominent benchlands at intervals for 50 miles along the central river course. These benches are best preserved from Golden Trout Creek northward. The highest determinable bench related to the present river direction is approximately 10,300 feet, near Junction Meadows (west of Mt. Whitney); its remnants appear at progressively lower elevations southward more than 40 miles. At Little Kern Plateau the surface lies at 6400 feet. This is Lawson's (1904) Chagoopa surface. Apparently the trend of the Kern was established early in the uplift of the Sierra Nevada; this conclusion suggests a zone of weakness existing at that time. The Chagoopa benchlands bevel Kern Canyon fault trace and are not now displaced. Therefore, the fault must have suffered final displacement prior to the development of the Chagoopa surface. An even more ancient date is suggested, because the fault (and river) cut diagonally across the Great Western Divide; this may mean the fault is pre-Divide in development.

Lawson's hypothesis is untenable in view of the ancient date of the last movement on the fault. His hypothesis was developed as a partial explanation of kernbuts. Lawson thought they represented down-dropped wedges in the graben itself. They are discontinuous, irregular in size, single and multiple blocks, separated from the adjacent canyon wall and from each other by passes or defiles which Lawson (1904, p. 332) designated kerncols. A glacial origin for kernbuts will be presented by Matthes in his report on glaciation of the upper Kern.

## DRAINAGE OF THE SOUTHERN SIERRA

Planation in the Sierra Nevada has been discussed by many writers (Le Conte, 1889; Lawson, 1904; Lindgren, 1911; Knopf, 1918; Matthes, 1930). Most workers infer that the southern Sierra Nevada possessed greater residual relief after widespread planation of the Nevadian Mountains than any other part of the range (Drake, 1897, p. 570; Lawson, 1904, p. 363; Hake, 1928, p. 1020; Matthes, 1930, p. 27; Miller, 1931, p. 334). The drainage pattern should be more stable, then, in the south, especially if structure controlled the original drainage. Therefore, the Kern might not have shifted from its southerly course during the westward tilt given by the Sierra Nevada fault, since the master drainage was established in pre-Chagoopa time when the region had considerable relief. Also, in the south, horst rather than tilted block structure is evident, since the Greenhorn fault system (Hake, 1928; Miller, 1931) developed on the west. Under such circumstances, then, a single master stream, anomalous in drainage direction among the master streams on the general Sierra Nevada block, might be expected.

## DEVIATION OF THE KERN FROM THE STRUCTURAL PATTERN

*General considerations.*—In two instances the Kern flows in marked discordance with the Kern Canyon fault: (1) at Grasshopper Meadows, and (2) near the mouth of the Little Kern. The stream flows south from Grasshopper Meadows without spe-

cific relation to the fault except for a single half-mile segment near the mouth of the Little Kern. In the upper Kern, both the Ancestral Kern Valley and Kern Canyon are fault-controlled; in the middle and lower Kern, the Ancestral Kern only is fault-controlled. At Grasshopper Meadows, where it first deviates from the fault line, the river turns east in a great sweeping bend, incised in a V-shaped gorge. Southward the gorge is replaced alternately by graded reaches and rock-walled narrows. At the junction with the Little Kern, the Kern River again follows the fault for nearly half a mile, then abandons it to swing west and flow continuously in a gorge to Fairview on the lower Kern.

Logically questions arise: (1) Where did the Kern flow in past cycles south of Grasshopper Meadows? (2) Why does the Kern deviate from the fault after following it for 30 miles from Junction to Grasshopper Meadows? (3) When was the diversion accomplished?

*Ancient drainage.*—Transverse profiles of the southern Sierra clearly suggest that early in the topographic history the Great Western Divide was a master drainage divide. Headward erosion through this divide occurred along a line of weakness occasioned by the Kern Canyon fault. River drainage transgressing the fault developed after the cutting through of the Great Western Divide, and before the close of the Chagoopa surface cycle. Superposition (by alluviation?) across the fault may have established the divergent course. Erosion through the divide prior to cutting of the Boreal surface, with superposition across the fault in the erosional period following the uplift of the Boreal surface, but before cutting of the Chagoopa surface, is another possibility. Boreal surface remnants have not been recognized along the Kern south of Golden Trout Creek.

Chagoopa benches, though restricted, occur in the segment where the Kern crosses the Great Western Divide. This prominent trans-drainage ridge, because of its original greater height, probably acted as a rock barrier through which the river flowed in narrows. Above and below the channel constriction caused by the divide, a wider valley was cut in the same time interval. At several places south of Golden Trout Creek narrow shelves or flat-topped spurs occur on the canyon slopes at levels appropriate to a southern continuation of the Chagoopa surface. Where the Little Kern joins the Kern prominent surfaces on and south of Little Kern Plateau lie at concordant levels. In the 18 miles from Golden Trout Creek to the Little Kern, remnants occur: (1) at 7500 feet on a prominent spur west of Kern Lake; (2) at 7500 feet on a nose 1½ miles south of Kern Lake on the east canyon slope; (3) at several localities on west slopes between Kern Lake and the head of Trout Meadows defile; such breaks are mere discontinuities in slope, but their elevations (7000-6700 feet) suggest their equivalence to more prominent benches to the north; (4) as terraces on spurs (a) between the Kern and head of Trout Meadows defile (6600), and (b) south of the Kern between Grasshopper Meadows and Nine Mile Creek (6400 feet); (5) as dissected benches at 5800 feet east of the Kern extending for a mile or more at Kern Flats; (6) as spurs at 5800-5500 feet south and east of the Kern at several places from Kern Flats to the Little Kern. Chagoopa benchlands are preserved beneath lava southeast of Kern River, and south of Rattlesnake Creek at 5500 feet. These remnants are too far east to have been cut by a stream flowing along the Trout

Meadows defile. By inference, then, all Chagoopa benches in the Ancestral Kern Valley were cut by a stream in essentially the position of the present Kern. If this explanation is accepted, then the Kern certainly transgressed Kern Canyon fault prior to development of the Chagoopa benchlands. Under this hypothesis direct evidence of the cause of deviation can scarcely be expected after vigorous and long-continued erosion. Lawson considered headward erosion as an explanation of the path of the Kern in a later stage of topographic development.

*Other suggestions.*—Chagoopa benchlands along the present Kern Canyon suggest that southern drainage of the Kern was established early in Sierran history. Lawson (1904), not emphasizing the importance of restricted benchlands south of Golden Trout Creek, considered several alternatives: drainage (1) northward through the present head of the Kern, (2) southward through Trout Meadows defile, (3) eastward through Toowa Valley (a) to Owens Valley via Templeton Meadows or via Templeton and Monachee meadows, or (b) to Little Kern via Monachee Meadows and Nine-Mile Canyon. The first alternative was discarded because of the persistent southward descent of the Chagoopa surface and because of no evidence of drainage reversal. The second alternative was discarded (a) because few Chagoopa benchlands were seen south of Golden Trout Creek, and (b) because Trout Meadows defile was shown never to have been occupied by a master stream. The third alternative was deemed the most likely, since Toowa Valley surfaces were essentially equivalent to the Chagoopa in elevation. A selection between 3(a) and 3(b) was not made.

Restricted Chagoopa benchlands along the Kern from Golden Trout Creek to Grasshopper Meadows are positive evidence for the southward flow of the Kern in the Chagoopa cycle. Furthermore, studies in Toowa Valley show that the valley drained westward when the Kern was graded to the Chagoopa surface, indicating the westward slope of Toowa Valley in the Chagoopa cycle.

### PRE-BOREAL PLATEAU DRAINAGE

*Importance of the Great Western Divide.*—Evidence suggests that the Great Western Divide represents the drainage divide of the pre-Chagoopa and possibly pre-Boreal cycles. (1) A broad open high-level valley paralleling the Great Western Divide on the northeast and extending southeastward from the headwaters of the South Fork implies an ancient drainage divide to the southwest for this region. (2) Trout Creek and other tributaries to the Kern and South Fork show peculiar drainage patterns (Fig. 4). Trout Creek heads on the east side of the Siretta Range, flows north, east, and southeast to join South Fork, which in turn flows south and west to join the Kern. Similarly Manter and Taylor creeks flow east of the Siretta divide to reach a master stream flowing west. (3) Gravels were deposited along the lower courses of these streams, particularly on Trout Creek. West-flowing streams in the region carry no gravels along their course; east-flowing tributaries of the Kern River show similar aggradation in their lower courses that may be due to the same cause. The present drainage divide, the crest of the Sierran escarpment, was formed during the first movement on the Sierra Nevada fault. The Siretta Range, locally with the highest elevations, was probably the former divide. Upon shift to the new divide, east-flowing streams were decelerated and forced to deposit, and west-flowing streams were

accelerated. Rapid uplift caused both east- and west-flowing streams to trench their channels, as suggested by goosenecks cut on South Fork between Manter and Taylor creeks; also gravels along east-flowing stream channels were trenched. The major result of divide shift was diversion of east-flowing streams to western drainage without shift of their headward segments.

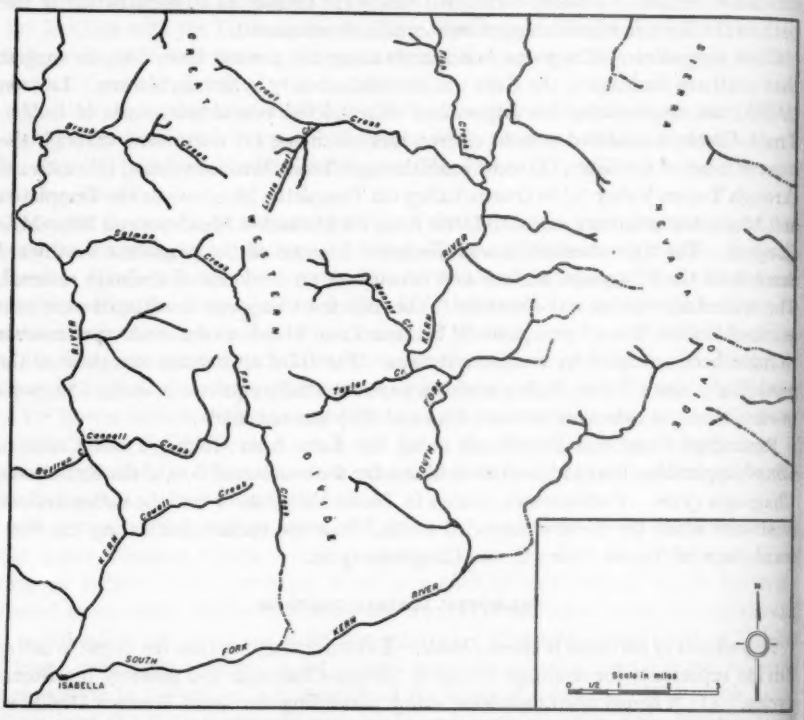



FIGURE 4.—*Drainage divides in the southern Kern Basin, Southern Sierra Nevada of California*

Studies of east-flowing streams from the present-day secondary (Great Western) divide suggest it was originally the primary one, but that it shifted eastward to the Sierra Nevada escarpment when faulting began. The South Fork flowed along the high valley (whose levels are preserved as suggested by the profiles, Plates 3 and 5) when the Great Western Divide was the master drainage division.

Evidence of a central divide following the Great Western Divide in the Nevadian Range is strongly suggestive. From other evidence Hake (1928) deduced a central divide which he though developed in the Tertiary rejuvenation of the Sierra. He suggests (domal) upwarp for the southern Sierra to extablish the Great Western Divide, followed by marginal block faulting, with faults of greatest magnitude on the east, producing a shift of divide. The present study supports the idea of shift, but

the central (Great Western) divide is thought to have been inherited from the Nevadian orogeny rather than to be the result of Sierran rejuvenation. Eastward migration of the crest in the central Sierra during rejuvenation was early recognized (Lindgren, 1911, p. 38–39) and is now generally accepted.

### CANYON STAGE OF THE KERN

*General characteristics.*—The Kern, at the close of the Chagoopa stage, is pictured as a stream graded nearly to its head, flowing in a wide rock-floored valley occasionally veneered with alluvium. The Canyon cycle began by uplift along the Sierra Nevada fault, during which streams were incised about 300 feet. These channels are preserved beneath lava flows of Little Kern Plateau and exposed in two places in the Little Kern Canyon wall. Accordance of master and tributary streams existed at the close of the Chagoopa cycle, so the Kern must similarly have been rejuvenated. Volcanism temporarily effaced the drainage of the Little Kern and Kern, at least as far south as Dry Creek. A segment of the Kern Canyon fault was also buried.

This volcanism must have dammed the main Kern, since the lavas extended far enough east to block the channel and at least to the 5500-foot contour, as shown by flow remnants south of Rattlesnake Creek. Prevolcanic channels of the Kern should not necessarily be preserved, since the present and prevolcanic channels must have been almost identical. Kern Flats, extending for nearly 3 miles along the Kern, is an aggraded segment lying headward close to the site of the volcanic dam. This aggraded area may date from the time of the volcanic dam.

Downcutting to present canyon level occurred as uplift continued by movements in the Sierra Nevada fault zone; lesser movements also occurred along numerous faults at the west base of the range.

*Origin of the Kern Canyon defile.*—Interesting drainage patterns developed in the Kern Basin, especially from the Little Kern to Kernville. Unequal erosion along the Kern Canyon fault and in Kern Canyon developed a high linear ridge which hugs the east wall of Kern Canyon. Early in the physiographic development of the Ancestral Kern Basin, probably in a pre-Chagoopa stage, Ancestral Kern Valley was graded to include the Kern Canyon fault. By the close of the Chagoopa cycle, a broad valley had developed which included the Kern Canyon fault at least from the Little Kern Plateau southward. After volcanism buried a segment of the Kern Canyon fault, rejuvenation by uplift on the Sierra Nevada fault superimposed the Kern River across, along, and parallel to the Kern Canyon fault. Except where the river flows along the fault, erosion by streams tributary to the Kern naturally followed the fault zone of weakness. As downcutting by the Kern continued, tributary streams, entering the river after crossing the fault line, developed subsequent tributaries along the fault at the points of crossing (Fig. 5). A defile in Kern Valley thus developed; at present the defile is about 1000 feet above Kern River. The divide between river and defile stands 3000 feet above the Kern Canyon floor from Little Kern Plateau south to Kernville.

*Origin of the Trout Meadows defile.*—Trout Meadows defile also is cut along the Kern

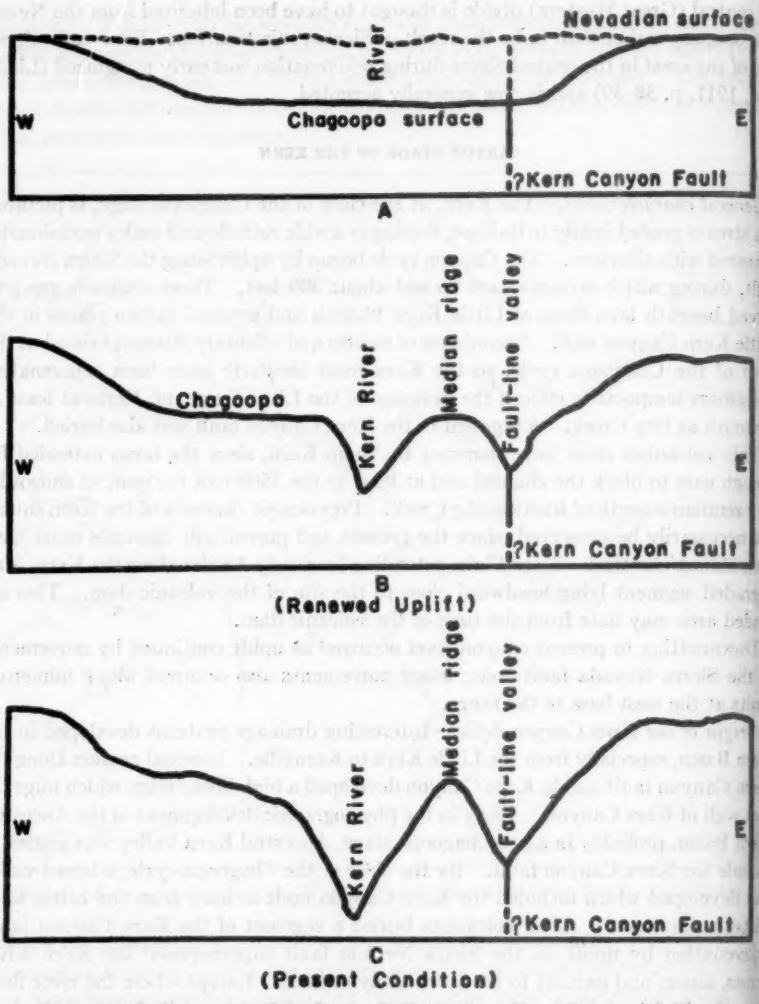



FIGURE 5.—*Evolution of the Kern Canyon Defile, Southern Sierra Nevada of California*

Canyon fault. In the initial, prevolcanic, post-Chagoopa canyon cycle, a tributary to the Little Kern followed the fault and began the defile. After volcanism, this stream was ponded locally. Downcutting by the Little Kern resulted in headward erosion of one of its tributaries, which now has tapped the Trout Meadows defile and is removing the swamp deposits, alluvium, and landslide material, accumulated since volcanism choked off its previous outlet.

## DRAINAGE OF TOOWA VALLEY

### GENERAL CHARACTERISTICS

Lawson (1904), pp. 319–322) first described Toowa Valley as follows:

"It is a high valley, geomorphically mature, which extends across the southern Sierra Nevada from the canyon of the Kern to a gap in the crest of the Summit Divide, about six miles west from the south end of Owen's Lake. . . . The floor of the valley is in two stages. The lower of these may be characterized as a broad, flat-bottomed succession of meadows and alluvial plains . . . [which] . . . do not fully occupy the floor, but are simply the lower part of a very wide valley. Looking toward the summit crest [of the Sierra, to the east] from the top of the cinder cone on the divide between Volcano [Golden Trout] Creek and the South Fork, Toowa Valley is for the most part a rocky platform of subdued, rolling relief, which forms a distinct terrace above the meadows which wind through it. This is the second stage of the valley floor. It is the breadth of this feature which gives the valley its expansive character. The flat bottom lands are a subordinate feature. The upper stage of the valley floor is more or less dissected, but in its general aspect it is a rocky surface of very gentle rise to the sides of the valley, where it merges by transitional slopes into the upland from which the valley has been carved."

The valley is excavated in quartz monzonite and granodiorite. Volcanic flows and cones of several ages, separated by erosional intervals, have locally ponded the drainage of the valley.

### LAWSON'S HYPOTHESIS OF THE ANCIENT DRAINAGE

Lawson (1904, p. 327) indicated the similarity of the Chagoopa Plateau levels of the upper Kern with those of Toowa Valley and suggested their correlation. He deduced also that the Toowa Valley levels were cut by the Kern, which, he postulated, must have then flowed eastward. This suggestion has never been tested and remains on the published record as an interesting speculation. After considering other possible drainage directions for this high-level valley, Lawson (1904, p. 327–28) concluded that:

". . . an outlet [for the Kern River] by way of Toowa Valley from the southern end of the plateau [upland surfaces of the Kern], has no inherent objection, and by elimination of the other two possibilities [northern and southern directions] seems the most probable hypothesis. In this event the drainage either followed Toowa Valley eastward to a gap in the summit crest, and thence out into the region of the Great Basin at the south end of Owens Lake, or it turned, following the course of the South Fork, and joined with the high valley represented by the Little Kern Plateau, lower down on the Kern . . . the extensive Monache Meadows [to the south] indicates that the South Fork traverses a valley which has characters similar to those of Toowa Valley, and, if this be true, then the ancient drainage probably followed that line.

"With the rapid downcutting of Kern Canyon, under the above hypothesis the upper [western] part of Toowa Valley was beheaded and the drainage of its upper part reversed."

Lawson (1904, p. 366) suggested that drainage reversal in Toowa Valley resulted from:

". . . down cutting of the Kern, below the floor of the High Valley [Chagoopa], [and] Toowa Valley was beheaded. This resulted from the capture of the drainage of Chagoopa Plateau by a stream heading up . . . from the point where the present Kern bends to the east below Lower [Little Kern] Lake."

Since Lawson considered the valley surface to have been cut in the Chagoopa cycle, the evidence of Chagoopa benches south of the junction of Toowa Valley and Kern Canyon establishes the westward flow of whatever stream occupied Toowa Valley during its cutting. This stream was a master tributary of the Kern River, joining at the present mouth of Golden Trout Creek.

### SHIFTING OF DIVIDES

In the Lawson hypothesis, the division of drainage in the Toowa Valley cycle was the Great Western Divide and the ridge summits north of Golden Trout Creek. However, the evidence points to a different conclusion.

Uplift on the Sierra Nevada fault which affected the eastern mouth of Toowa Valley caused downcutting in the post-Toowa Valley cycle. Continued uplift tilted the Sierran block westward. With the initial uplift, the division of drainage of a supposedly eastward-flowing stream of the gradient of Toowa River should have shifted from a western position to one coincident with the divide at the summit of the newly formed escarpment. The drainage relations today show that the erosional capacity of Toowa River was insufficient to overcome the adverse tilt of the rising Sierran block. The division of drainage of Toowa Valley now lies 8 miles west of the escarpment summit; in 6 of these 8 miles, the stream draining the valley has cut only 100 feet below the present-day divide. By what mechanism was the divide shifted from its inevitable escarpment position (the one held by most streams in the region) to its present central position? The logical conclusion is that the divide never occupied the escarpment position during Toowa Valley cutting but had essentially the present position in the Toowa. Shifting of a central divide is recorded in present-day drainage changes, but no eastern divide is possible under the physical conditions suggested by the evidence. In the Toowa Valley cycle, then, the divide was always central and was never near its western margin. The drainage of Toowa Valley has by this view been always westward rather than eastward, even at the time of original cutting.

An alternative but less likely view is simply that Toowa Valley was cut by two streams flowing respectively east and west from a central divide. The ability of two oppositely flowing streams to cut two such accordant valleys is clearly demonstrated, since the inner Toowa Valley is cut by two such streams working in the present cycle.

### DRAINAGE CHANGES IN PRESENT CYCLE

The Olancha topographic map shows the unusual drainage pattern of present streams in Toowa Valley. The eastern (South Fork) drainage pattern is particularly anomalous with drainage ponding and underfit streams. The pattern is closely related to changes in temporary local base level, which occasioned the shifting of the divide between the present-day Golden Trout Creek and South Fork. These shifts were caused largely by volcanic interference in the evolution of normal drainage of the two master streams.

After the initial upward movement on the Sierra Nevada fault, the mountain block continued to rise and tilt westward faster than the downcutting rate of east-flowing streams. Eastward-flowing streams were graded, therefore, to the lower courses of their own drainage, now at elevations of 8500 to 9000 feet. Westward-flowing streams were accelerated and downcut rapidly, developing canyon cycles on streams like Golden Trout Creek. During this canyon-cutting episode, Golden Trout Creek established a new base level at 6450 feet, where it joined its master, Kern River. At this time Golden Trout Creek drainage included (1) the present South Fork northeast of Tunnel Meadows, and (2) north- and south-flowing tributaries of South Fork to the

east end of Ramshaw Meadows (Pl. 6, stage I). The present drainage pattern, the sharp direction reversal of South Fork at Tunnel, and direction changes of tributary streams in relation to the present South Fork suggest this fact.

Had these topographic conditions continued, Golden Trout Creek would have diverted the drainage of South Fork until the Sierran escarpment became the drainage divide of Toowa Valley. However, flows moved westward in the canyon cut by Golden Trout Creek, interrupted drainage, and established several new temporary local base levels. Flows filled the canyon, and volcanic cones interrupted the drainage, so that the effective base level was changed from 6450 feet at Kern River to 8850 feet at Golden Trout Creek below the present divide in Toowa Valley.

With this rising base level on Golden Trout Creek, the east-flowing South Fork, graded to a temporary base level of 8600 feet, became the more powerful of two weakly downcutting streams (Pl. 6, stage II). The resulting headward erosion of South Fork captured tributaties of Golden Trout Creek, until an important capture occurred at the present divide of the two streams, whereby South Fork acquired the drainage of Tunnel Meadows and its headwaters (Pl. 6, stage III).

This interpretation is supported by (1) the underfit character of Golden Trout Creek in its valley just below the elbow of capture at Tunnel; (2) small water-worn pebbles along a swale in the tunnel divide, lying in the projected position of the captured segment of Golden Trout Creek (now the headwaters of the South Fork); and (3) barbed tributaries.

As the capture at Tunnel approached (Pl. 6, stage II), Mulkey Creek, a northern tributary of South Fork, cut headward from Templeton Meadows and diverted the drainage of Mulkey Meadows southward. Mulkey Meadows had formerly drained westward through Tunnel Meadows into Golden Trout Creek. This diversion occurred probably before the actual capture at Tunnel, because less work was needed to divert these waters, the distance being 4 and 10 miles, respectively, with 900 feet of fall in each case.

### FUTURE DRAINAGE CHANGES

In view of the slow rate of reduction of Golden Trout Creek to its ultimate 6450-foot base level, the superiority of South Fork in downcutting power will dominate for some time. Golden Trout Creek has cut only a small gorge in the volcanic rocks, and future volcanism in the stream bed may increase the work to be accomplished. Therefore, capture of the remaining Golden Trout Creek headwaters is imminent (Pl. 6, stage III); diversion was accomplished artificially about 1880 when a tunnel was driven through the narrow drainage divide to divert the headwaters of Golden Trout Creek into South Fork. Legal action forced abandonment of this artificial capture, and the waters were returned to their natural courses. Capture would have undoubtedly occurred before now, had it not been for some minor volcanic accumulations in South Fork, 300 yards below the last elbow of capture, that retarded destruction of the narrow divide. After the approaching capture of Golden Trout headwaters occurs, it is inevitable—barring further volcanism in Lower Golden Trout drainage—that the weakened stream will, in spite of reduced volume, recapture all

its lost headwaters, since the base level of its master stream is so much lower than that of South Fork.

However, increased downcutting of the streams flowing east over the Sierran escarpment, graded to Owens Valley at 3500 feet, may accelerate sufficiently to capture South Fork drainage. If so, then present drainage trends of Toowa Valley will be maintained.

## AGE OF GEOLOGIC EVENTS

No new evidence suggesting age assignments for the geologic and geomorphic events was found. Current age assignments for petrologic events are summarized by Hinds (1934), Taliaferro (1942, pp. 95–105), and others; and for geomorphic events by Lawson (1904, pp. 362–368) and Matthes (1930, pp. 22–23; 1933, pp. 26–39). Opinions on the age of Sierran upland surfaces vary widely, and since the writer can add nothing new to the meager data available no inferences will be attempted.

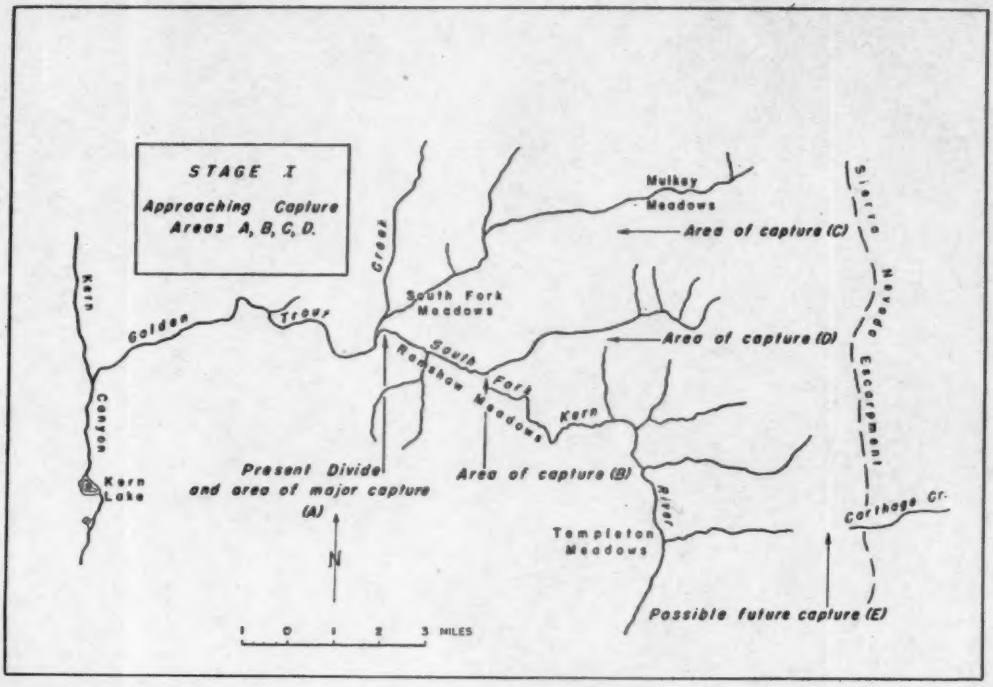
## PROBLEMS FOR FUTURE STUDY

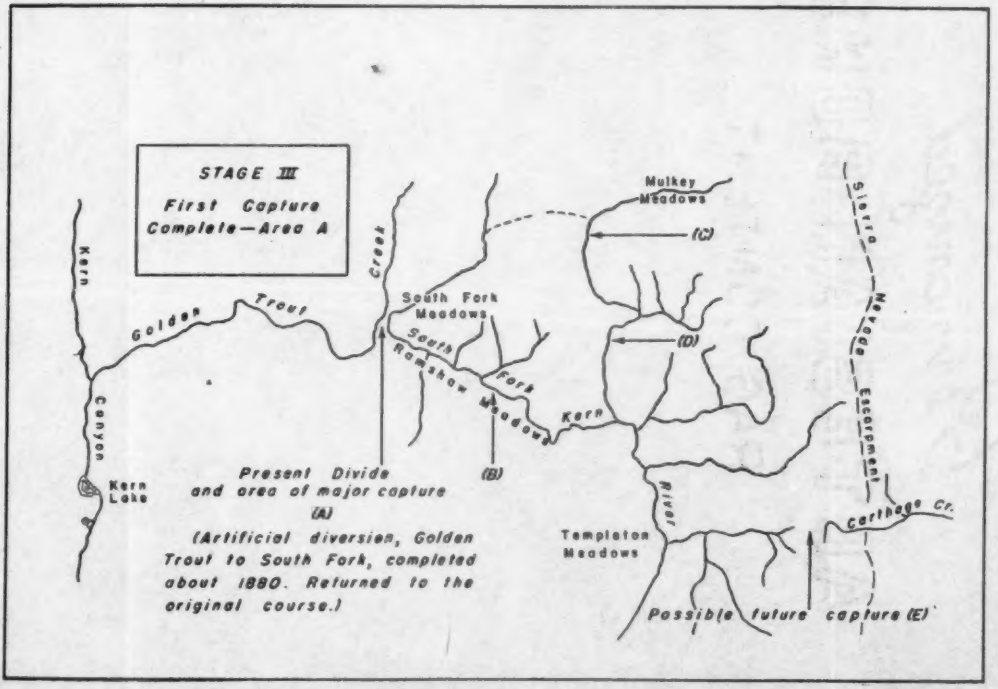
Two important topographic features of the Kern Basin have been neglected in this treatment: (1) origin of South Fork Valley, and (2) origin of the extensive pattern of upland meadows so prominent in the southern Sierra. It seems best to omit these features, since data on their origin are meager. At the present writing, the origin of South Fork Valley is still exceedingly obscure. Detailed mapping on new aerial mosaics in the area of confluence of Kern and South Fork rivers may provide an explanation. Interpretation of the upland meadows should logically await completion of field work in more of the southern Sierra.

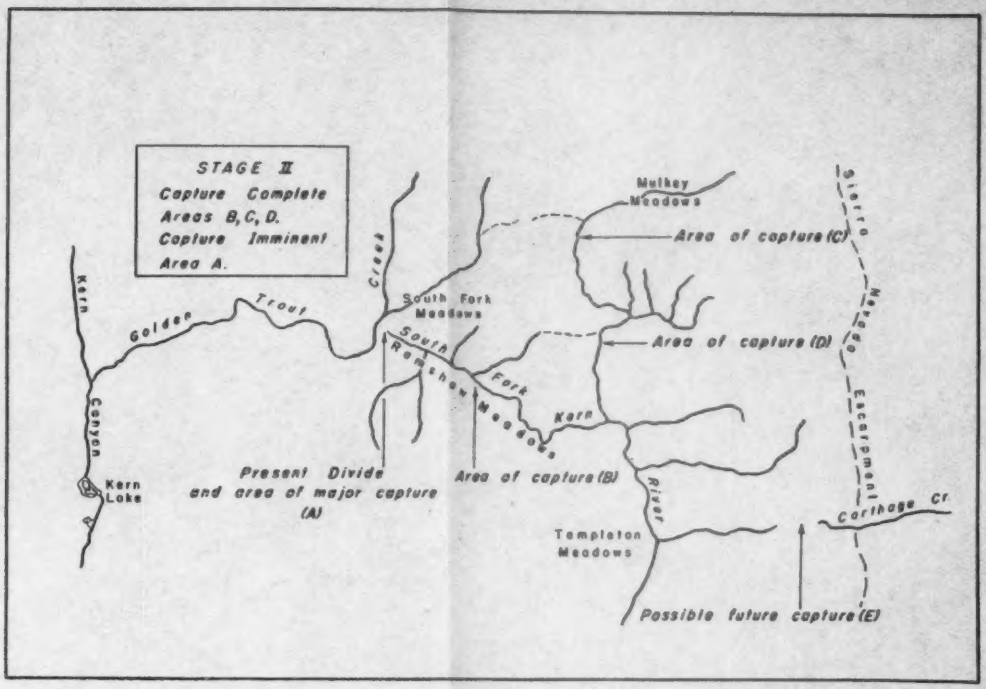
Similarly, further work is necessary before the explanations given for the evolution of the Kern Basin may be applied to the entire southern Sierra. The major theses of this paper appear to be applicable to the larger region, but it would be gravely premature to extend these interpretations to adjacent regions before making more detailed field studies than those now completed.

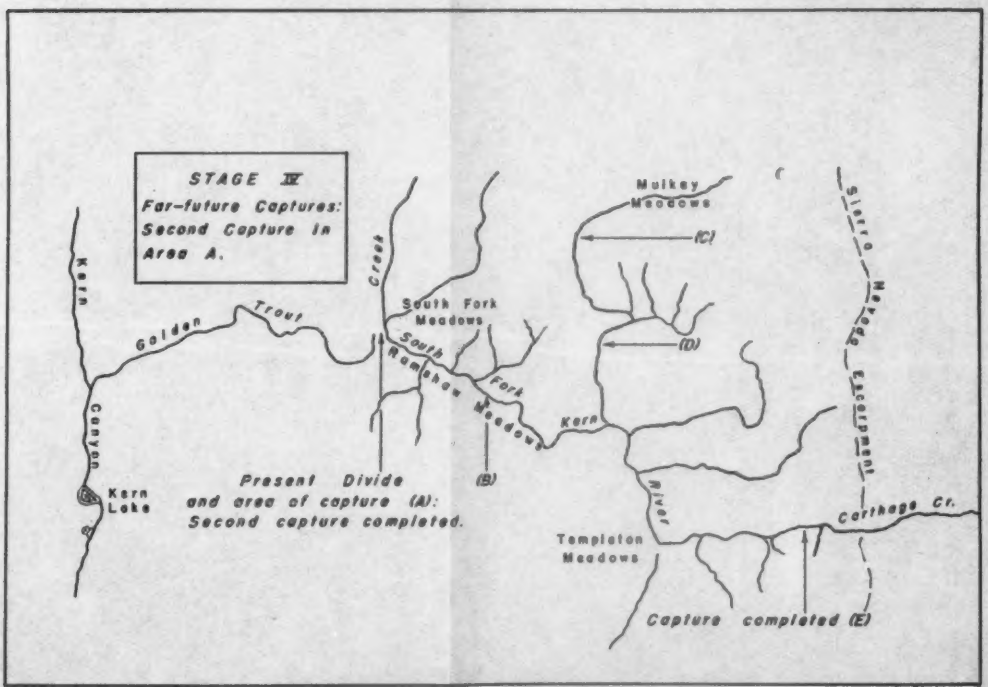
## CONCLUSIONS

The Middle Kern Basin has been drained since the close of the Nevadian orogeny by a south-flowing master stream. The Great Western Divide, now transgressed by the Kern, is interpreted as an original master drainage divide of the Nevadian Mountains. Headward erosion through the Great Western Divide occurred along a zone of weakness occasioned by the Kern Canyon fault. The fault is inferred to be of ancient date, produced probably in the Nevadian orogeny. This inference is based on relationships of old land surfaces, residuals of which are preserved along ancient Kern channels. Volcanic episodes occurred between development of erosion surfaces and preserve a record which strengthens the interpretation that the Sierra was built by several component movements on the Sierra Nevada fault. Evidence of at least one hitherto unrecorded period of canyon cutting is found, buried beneath the volcanic flows, exposed in the canyons of the Kern and its tributaries. Temporary diversion of drainage was occasioned by volcanism both along the Kern and in its


STAGE I
Approaching Capture
Areas A, B, C, D.
Kern
Golden
Trout
Creek
South Fork
Meadows
Mulkey
Meadows
Area of capture (C)
Sierra
Nevada
Escarpment
Area of capture (D)
South
Fork
Kern
River
Rattlesnake Meadows
Kern
Canyon
Kern
Lake
Present Divide
and area of major capture
(A)
Area of capture (B)
Templeton
Meadows
Carthage Cr.
Possible future capture (E)
N
1 0 1 2 3 MILES


STAGE III
First Capture
Complete—Area A
Kern
Golden
Trout
Creek
South Fork
Meadows
Mulkey
Meadows
(C)
Sierra
Nevada
Escarpment
(D)
South
Fork
Kern
River
Rattlesnake Meadows
Kern
Canyon
Kern
Lake
Present Divide
and area of major capture
(A)
(B)
(Artificial diversion, Golden
Trout to South Fork, completed
about 1880. Returned to the
original course.)
Templeton
Meadows
Carthage Cr.
Possible future capture (E)




VALLEY, SOUTHERN SIERRA NEVADA OF CALIFORNIA

Toowa Valley tributaries. Volcanism, and periodic movement on the Sierra Nevada fault, produced other drainage changes. The impossibility of eastward drainage of the Kern through Toowa Valley into Owens Valley, as suggested by Lawson (1904), is demonstrated.

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University of California, Los Angeles.
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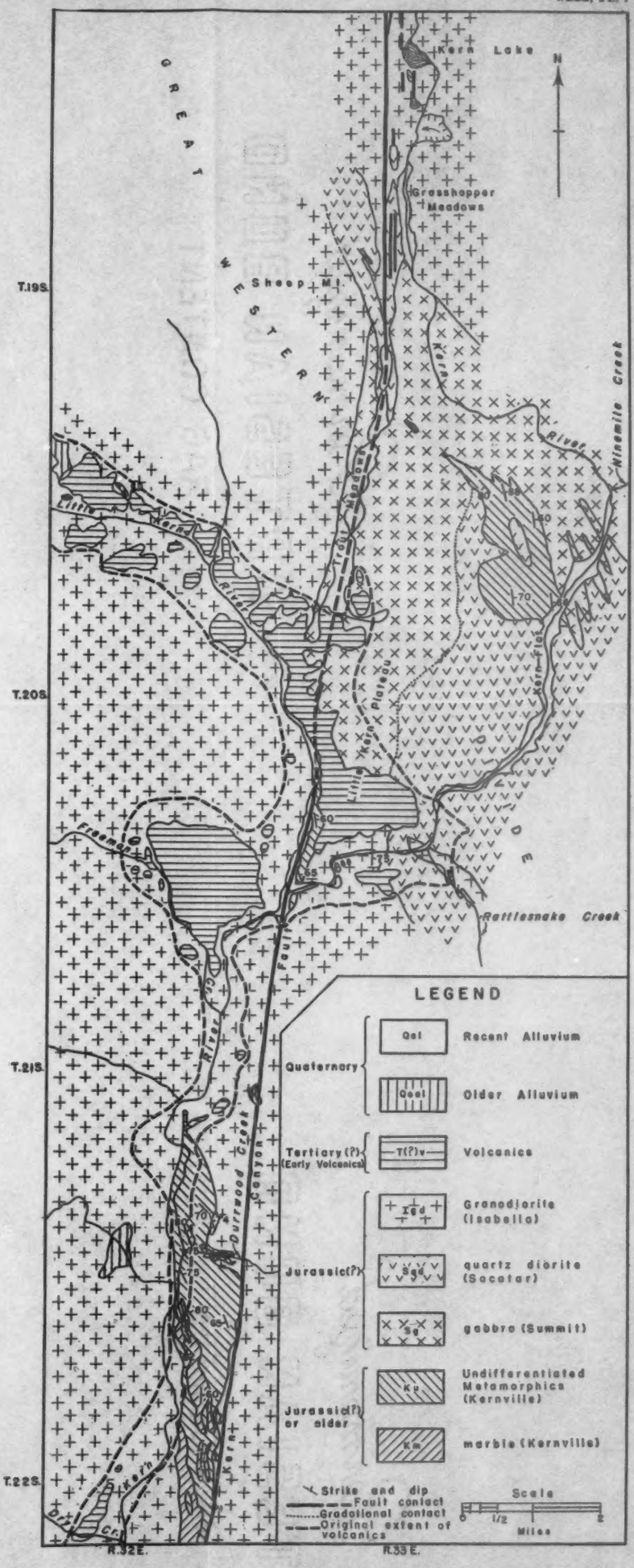
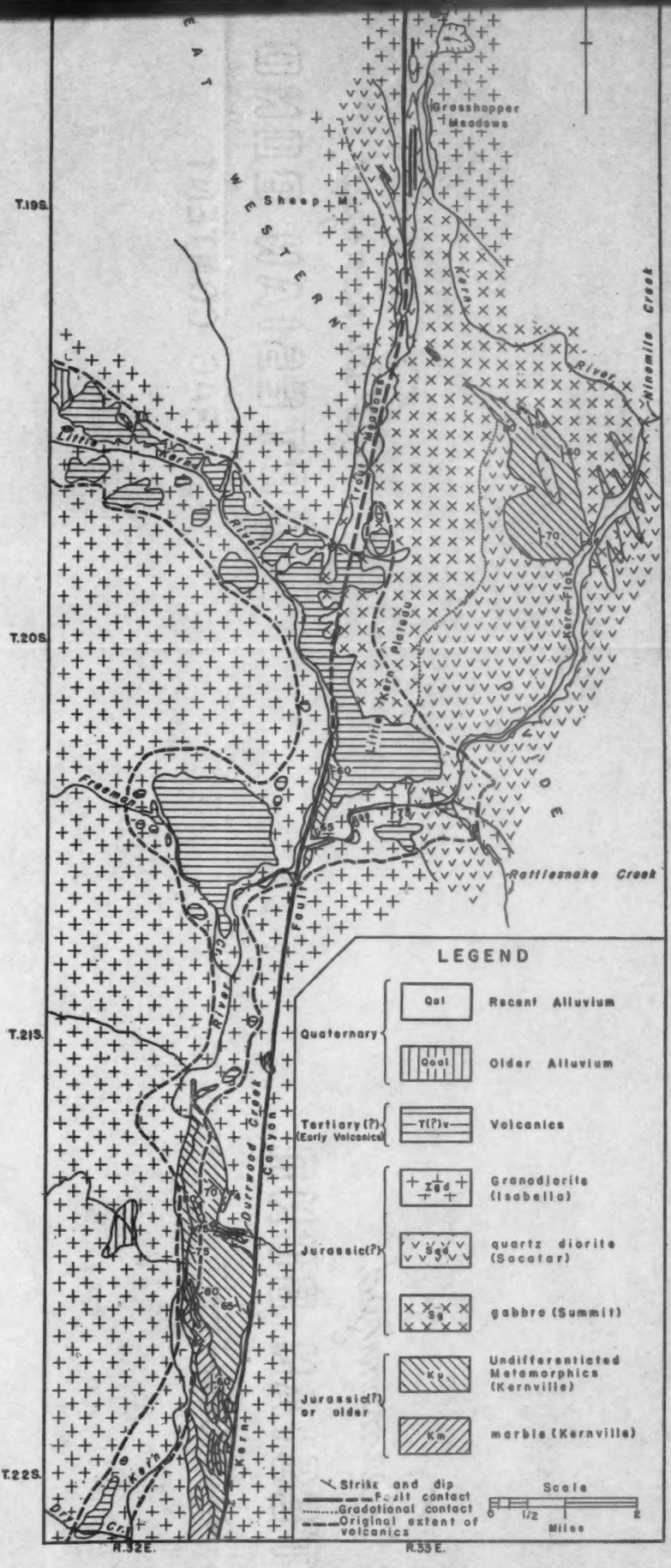
Presented in Part Before the Cordilleran Section, April 17, 1936, and April 17, 1942.




## GEOLOGIC MAP OF THE MIDDLE KERN BASIN, SOUTHERN SIERRA NEVADA OF CALIFORNIA

*Kern River:* The descent of the Kern River through alternate gorge and graded reach topography as far as the junction with the Little Kern is clearly shown. The steep profiles of Durrwood, Brush, Salmon, and Cannell creeks, which descend the fault-line scarp from the east to join the Kern, are in sharp contrast to those profiles of western tributaries, indicating the asymmetry of Kern Canyon. The effects of some remnants of the Boreal erosional surface are

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*South Fork:* The interpretation that the South Fork developed a course across erosional levels of earlier cycles is supported by the profiles of the stream and its tributaries. It is notable that South Fork from the Olancha-Kernville quadrangle boundary nearly to its head crosses the Boreal erosional surface, and that the same surface finds expression in the broken profiles of Fish, Trout, Manter, and Taylor creeks. Likewise the profile segment from the junction of Fish Creek to Manter Creek reflects what is considered the equivalent of the Chagoopa erosional surface.

## RESEARCH FELLOWSHIPS

Research Fellowships for graduate study, and Graduate Assistantships, are open in Missouri School of Mines and Metallurgy to properly qualified applicants. Graduate work may be done leading to the Ph.D. degree or Master of Science degree in Mining, Metallurgy, Ceramics, or Geology. Further details concerning these opportunities may be obtained from Professor J. D. Forrester, Chairman, Committee on Graduate Study, Missouri School of Mines, Rolla, Missouri.

## OFFICIAL CALENDAR

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| May 3 | National Research Council meeting, Washington, D. C. |
| May 25–26 | Geological Society Northeastern Section, Field meeting, Bethlehem, Penna. |
| May 27–29 | American Geophysical Union meeting, George Washington University, Washington, D. C. |
| May 30–June 2 | Field Conference of Pennsylvania Geologists, State College, Penna. |
| September 15 | Final date for submission of project applications for action in October |